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EXPLOSIVE DITCHING WITH TNT

by

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Final Report

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WES

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Errata Sheet

No. 1

EXPLOSIVE DITCHING WITH TNT

Miscellaneous Paper N-77-7

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1. The equation in line 10, page 41, should read as follows:

$$n = \left(\frac{L}{S}\right) + 1 = \frac{2000}{5} + 1 = 401$$

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TNT

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report enables the comparison of data being developed on new commercial explosives with the military standard TNT explosive. The report presents the current definitions for single and row craters and the soils and rocks classification system for explosive excavation purposes.

The theoretical basis for predicting and designing excavations by means of explosives is developed. Field data for nine different media were reexamined and submitted to a statistical analysis following preestablished criteria.

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20. ABSTRACT (Continued).

The results of this analysis, along with the parameters for optimum charge burial depth for each medium, are presented in graphic form. Smoothness conditions are established for ditching designs, and some sample calculations of single and row craters are presented. Appendixes A and B present crater dimensions from single high-explosive charge detonations in rock and in soil, respectively. Appendix C gives ditch dimensions from high-explosive row-charge detonations in rock and soil.

PREFACE

This study was conducted during FY 1976 and the T-Quarter under the sponsorship of the Office, Chief of Engineers, U. S. Army, as a part of the Military Engineering Applications of Commercial Explosives (MEACE) program under Project 4A762719AT40, "Mobility, Soils, and Weapons Effects Technology," Task A1, Work Unit 012. Because of the importance of the explosive TNT as a standard for cratering studies, a meticulous reexamination was made of all available TNT data. These data were converted to the metric system of measurement to allow their direct comparison with data being developed on newer explosives during field tests of the MEACE program. Finally, a uniform application of appropriate computer techniques was made to all of the TNT data. This report has been formatted to be of maximum usefulness to field engineers.

MAJ Arno M. Müller, a Brazilian exchange officer assigned to the Explosive Excavation Division (EED), Weapons Effects Laboratory (WEL), U. S. Army Engineer Waterways Experiment Station (WES), conducted the study and wrote this report under the supervision and with the assistance of Mr. H. D. Carleton, EED, Project Manager for the MEACE program.

Chiefs of EED during the study were MAJ L. C. Webster and Mr. J. W. Brown; Chief of WEL was Mr. W. J. Flathau.

Directors of WES during the conduct of this study and the preparation and publication of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, METRIC (SI) TO U. S. CUSTOMARY AND U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

Units of measurement used in this report can be converted as follows:

Multiply	By	To Obtain
Metric (SI) to U. S. Customary		
millimetres	0.03937	inches
metres	3.28084	feet
cubic metres	35.31467	cubic feet
kilograms	2.20462	pounds
metres per kilogram$^{1/3.0}$	31.8	feet per ton$^{1/3.0}$
metres per kilogram$^{1/3.2}$	27.6	feet per ton$^{1/3.2}$
metres per kilogram$^{1/3.4}$	24.3	feet per ton$^{1/3.4}$
kilopascals	0.1450377	pounds (force) per square inch
U. S. Customary to Metric (SI)		
inches	2.54	centimetres
pounds (mass)	0.4535924	kilograms

EXPLOSIVE DITCHING WITH TNT

PART I: INTRODUCTION

Purpose and Scope

1. This report is a guide to the calculation and positioning of TNT charges for cratering and ditching purposes. It is intended to summarize in one publication all information necessary for the prediction and design of TNT craters in a variety of earth materials. Since the included design methods are empirically based, the number of earth media to be included has necessarily been based upon the availability of experimental data.

Background

2. Since the first systematic investigations of the cratering effects of large TNT charges began during World War II, a variety of cratering tests have been conducted. The earliest experiments were concerned primarily with the effects of bomb detonations near structures. These early tests led in the late 1940's to the U. S. Army Corps of Engineers Underground Explosion Test Program involving spherically stacked TNT charges in a variety of earth media. Emphasis in these later tests was placed upon the development of design criteria for explosion-resistant underground structures. Also in the late 1940's, a series of TNT cratering tests, the Panama Canal Company's Isthmian Canal Study, was conducted in the Panama Canal Zone to determine the Canal's vulnerability to attack by nuclear weapons.

3. TNT cratering tests continued to be an important part of weapons effects studies into the 1950's and 1960's. In addition, TNT cratering and ditching tests were the predominant experiments during the early stages of the U. S. Atomic Energy Commission's Plowshare Program in the 1960's. Though a shift to other chemical explosives for ditching

experiments began during the 1960's and has continued since, TNT is still the only explosive that has a data base broad enough to establish it as a standard for the evaluation of all other cratering explosives.

Cratering Definitions

4. The following definitions, most of which are illustrated in Figure 1, are commonly used in explosive excavation literature.[1-3]

a. True crater. The boundary of the crater representing the limit of dissociation of the medium by the explosion.

b. Apparent crater. Portion of the visible crater below the original ground surface elevation.

c. Apparent lip. Portion of the visible crater above the original ground surface elevation. It is composed of two parts: upthrust (true lip) and ejecta.

d. Upthrust. Material that has been permanently displaced above the original ground surface elevation.

e. Ejecta. Material permanently ejected from the true crater void by the explosion.

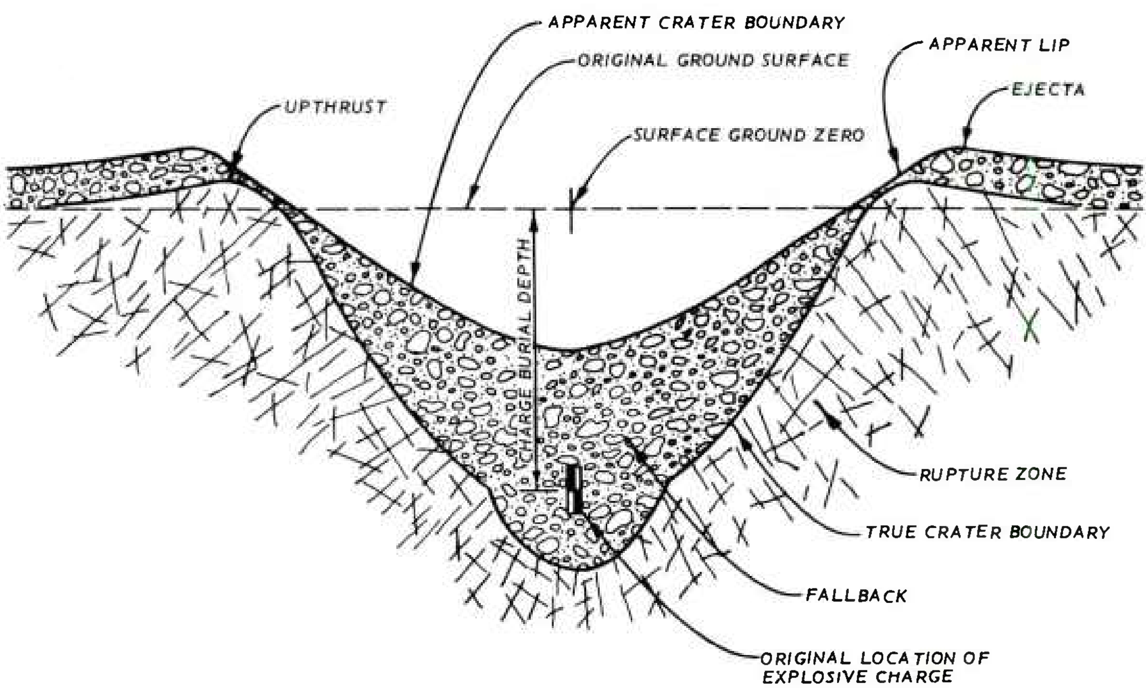

Figure 1. Cross section of typical crater in rock, showing nomenclature

f. Fallback. Material dissociated by the explosion that has fallen back within the true crater void.

g. Rubble. Material comprising the fallback and ejecta.

h. Rupture zone. The zone of blast-induced fractures and displacement from true crater boundary outward to the relatively undisturbed in situ material.

i. Charge burial depth. The emplacement depth at which the charge is fired.

j. Optimum charge burial depth. The emplacement depth that produces the largest possible crater.

k. Row shot. A multiple explosion with the charges emplaced in a linear array (row of charges).

l. Row crater. A ditch or canal formed by the detonation of charges emplaced in a row shot geometry.

Influence of Charge Burial Depth on Crater Formation

5. From the cratering standpoint, the charge burial depth* B is the distance from the center of mass of the charge to the original ground surface. For a given weight of charge, variation in the charge burial depth will result in craters of differing shapes and dimensions. A surface burst ($B = 0$) forms a shallow depression by crushing, compacting, and scouring the material below the explosion (Figure 2a). At a shallow B the material is thrown out with high velocity, increasing the ejecta volume, and very little material falls back (Figure 2b). When the maximum amount of material is thrown out of the crater and maximum crater dimensions are reached, the corresponding burial depth will be the optimum (Figure 2c). Below this optimum B, a larger quantity of material will be disturbed, but very little of it will be ejected; instead, a crater mound will result from fallback (Figure 2d). If B is increased to the depth at which no fragmented material is thrown out, the contained explosion will create a cavity by compaction and collapse of the disturbed material (Figure 2e).

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* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix D).

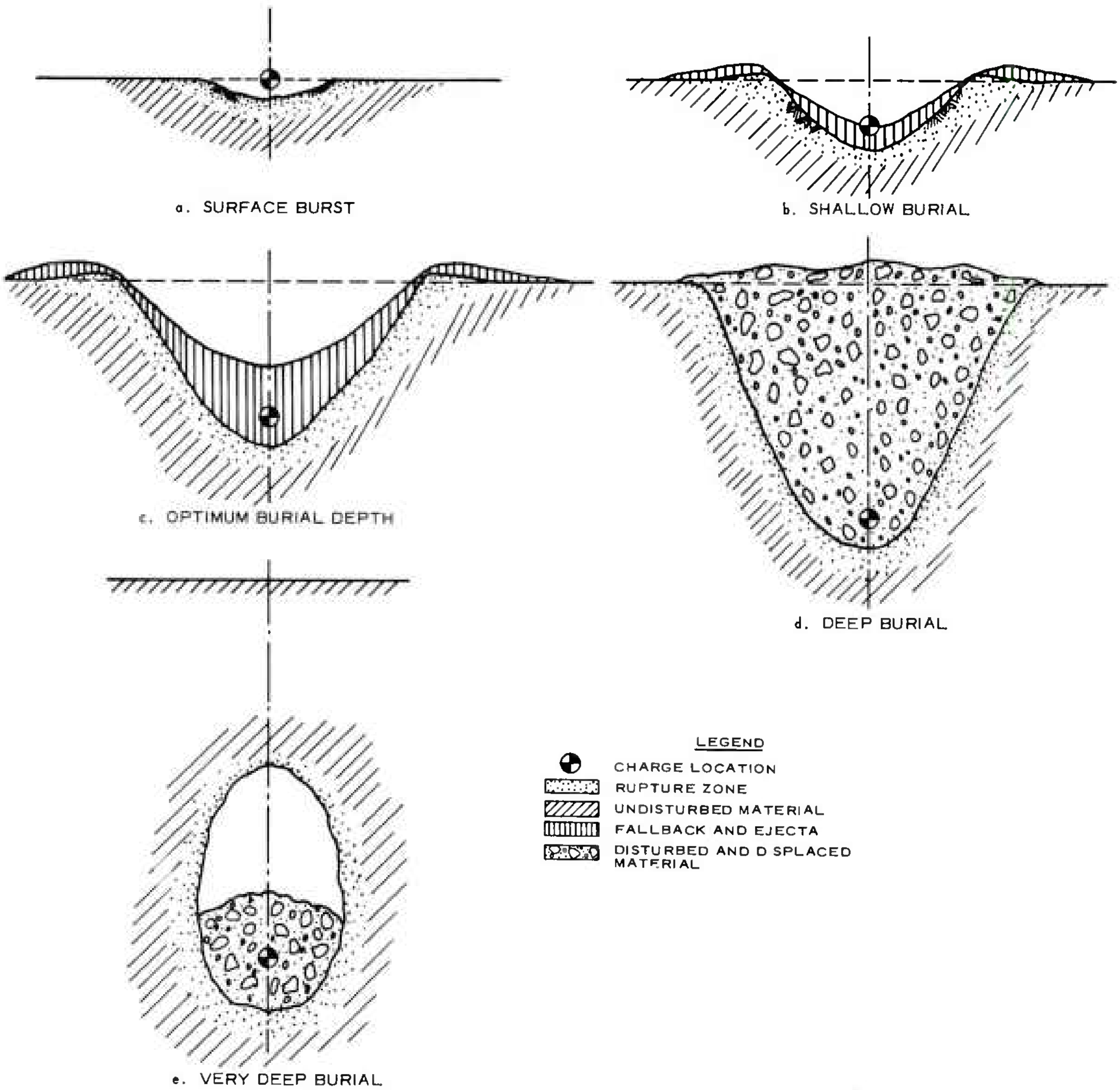


Figure 2. Crater profiles as a function of burial depth for the same weight of charge

Classification of Cratered Media

6. The available media classification system for explosive excavation in rock[4,5] and the Unified Soil Classification System[6] were used as much as possible to define the media for which data were analyzed in this report (Tables 1 and 2).

7. The following rock and soil types will be covered in this report. An adjective describing degree of saturation has been added to each soil's designation.

Type	Classification
Rock	
Basalt	High-strength rock
Granite	High-strength rock
Sandstone	Intermediate-strength rock
Weak sandstones and shales	Weak rock
Soil	
Dry gravelly sand	Coarse-grained soil (GW)
Dry sand	Coarse-grained soil (*)
Dry sandy clay	Coarse-grained soil (SC)
Wet clay	Fine-grained soil (OH and MH)
Saturated silty clay	Fine-grained soil (*)

* Gradation, plasticity index, and liquid limits unknown.

PART II: SINGLE-CRATER DESIGN

8. Criteria for the design of single craters by the use of empirical scaling relationships are developed in the following paragraphs. While single-crater design may be an object in itself, it is more likely in engineering applications that ditching designs will be desired. This part therefore derives its primary importance from the fact that single-crater design is basic to explosive ditching design.

9. Computer programs are available that use calculations of mound and cavity growth with a free-fall throw-out model to give cratering phenomena predictions. However, the empirical scaling method offers accuracy comparable to that of computerized methods,[3,7] and is much more convenient and suitable for the use of engineers in the field. Discussions in this report will be limited to those necessary to convey to the prospective user an understanding of the empirical scaling method of crater design.

Theoretical Basis

10. The basic premise of the empirical scaling method is that the ratio between the apparent linear dimensions of two craters caused by the same type explosive in the same medium will be equal to the ratio between the charge weights raised to a power:[8]

$$\frac{x_1}{x_0} = \left(\frac{w_1}{w_0}\right)^{1/a} \tag{1}$$

where

x_1, x_0 = linear dimensions of the compared craters
w_1, w_0 = corresponding charge weights
$1/a$ = power to which charge weights are raised

For cratering with conventional explosives, the value of a ranges between 3.0 and 3.4, depending upon the characteristics of the cratered

medium. The value of a may range up to 4.0 when the cratering effects of nuclear devices are considered.[3,8]

11. By extension of the preceding premise, the ratio between the apparent crater volumes of two craters caused by the same type explosive in the same medium will be equal to the ratio between the charge weights raised to a power equal to three times the power of the corresponding relation for the linear dimensions:

$$\frac{V_1}{V_0} = \left(\frac{w_1}{w_0}\right)^{3/a} \tag{2}$$

where V_1 and V_0 are the apparent crater volumes.

12. Equations 1 and 2 can be rewritten to introduce coefficients as follows:

$$x_1 = c_x w_1^{1/a} \quad , \quad \text{where} \quad c_x = \frac{x_0}{w_0^{1/a}} \tag{3}$$

$$V_1 = c_v w_1^{3/a} \quad , \quad \text{where} \quad c_v = \frac{V_0}{w_0^{3/a}} \tag{4}$$

where

c_x = coefficient for linear crater dimension

c_v = coefficient for apparent volume of single crater

The coefficients c_x and c_v and the exponent $1/a$ can be calculated from experimental data. The coefficients will be different for different media and moisture contents, and for different explosives. Once these coefficients and the exponent become available for any given explosive and medium, however, cratering dimensions or volumes may be predicted for any desired charge weight using the simple relationships:

$$x = c_x w^{1/a} \tag{5}$$

and

$$V = c_v w^{3/a} \tag{6}$$

where $1/a$, the exponent, and the c coefficients are known quantities. Transposing Equations 5 and 6 will also make possible the determination of the charge weights required to produce craters of required sizes:

$$w = \left(\frac{x}{c_x}\right)^a \tag{5a}$$

and

$$w = \left(\frac{V}{c_v}\right)^{a/3} \tag{6a}$$

Scaled Dimension Plots

13. The linear dimensions of primary interest for cratering purposes are apparent crater radius R , apparent crater depth D , and charge burial depth B , shown in Figure 3. Coefficients can be computed

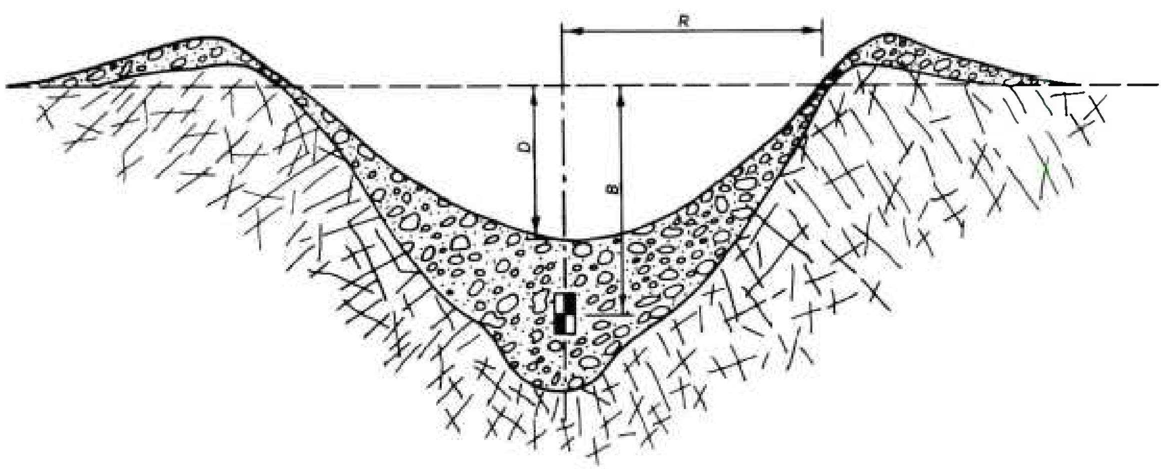


Figure 3. Cross section of a single crater

for B , R , D , and V for each experimental crater that results

from a specific combination of explosive and medium after the manner used for Equations 3 and 4:

$$c_b = \frac{B}{W^{1/a}} \tag{7}$$

$$c_r = \frac{R}{W^{1/a}} \tag{8}$$

$$c_d = \frac{D}{W^{1/a}} \tag{9}$$

$$c_v = \frac{V}{W^{3/a}} \tag{10}$$

These coefficients represent the scaled dimensions of the crater actual dimensions. These computations will allow a direct comparison of the cratering effects from charges of various weights, so that the effects of charge burial depth variation can be isolated and studied. Scaled dimensions for all craters within the group to be studied can be plotted on a Cartesian coordinate system to quantify the manner in which crater dimensions vary with changes in charge burial depths. As an example, the curve in Figure 4 (which represents a low-order polynomial function fitted to experimental data points by a least-squares fit) shows the dependence of scaled apparent radius on scaled charge burial depth for a hypothetical explosive/medium combination that scales at $a = 3.4$. The largest possible crater radii for this explosive in this medium will occur at burial depths corresponding to the scaled charge depth value c_b, indicated by the arrow at the peak of the curve. The prediction for the radius to be achieved by a given charge weight buried at this scaled depth will be based upon the value of c_r at this point. Both the required burial depth and the predicted crater radius could be calculated from Equation 5 for any given charge weight by appropriate substitution of the values of a, c_b, and c_r given in Figure 4.

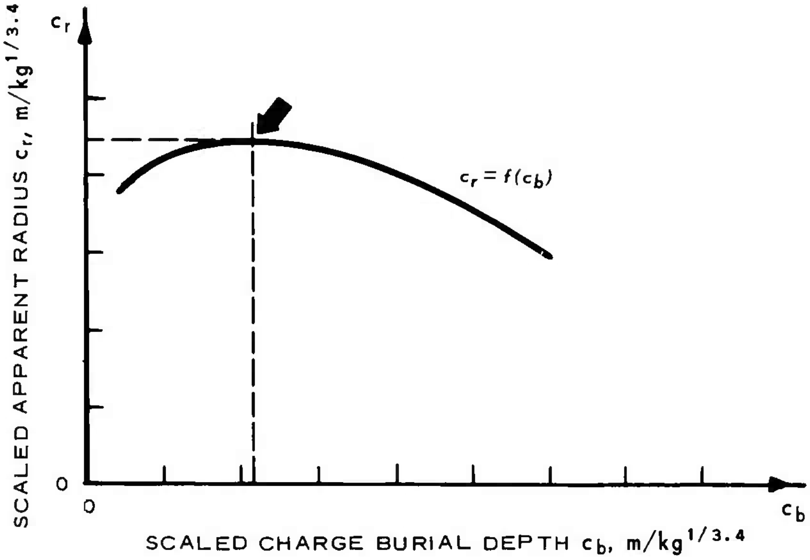


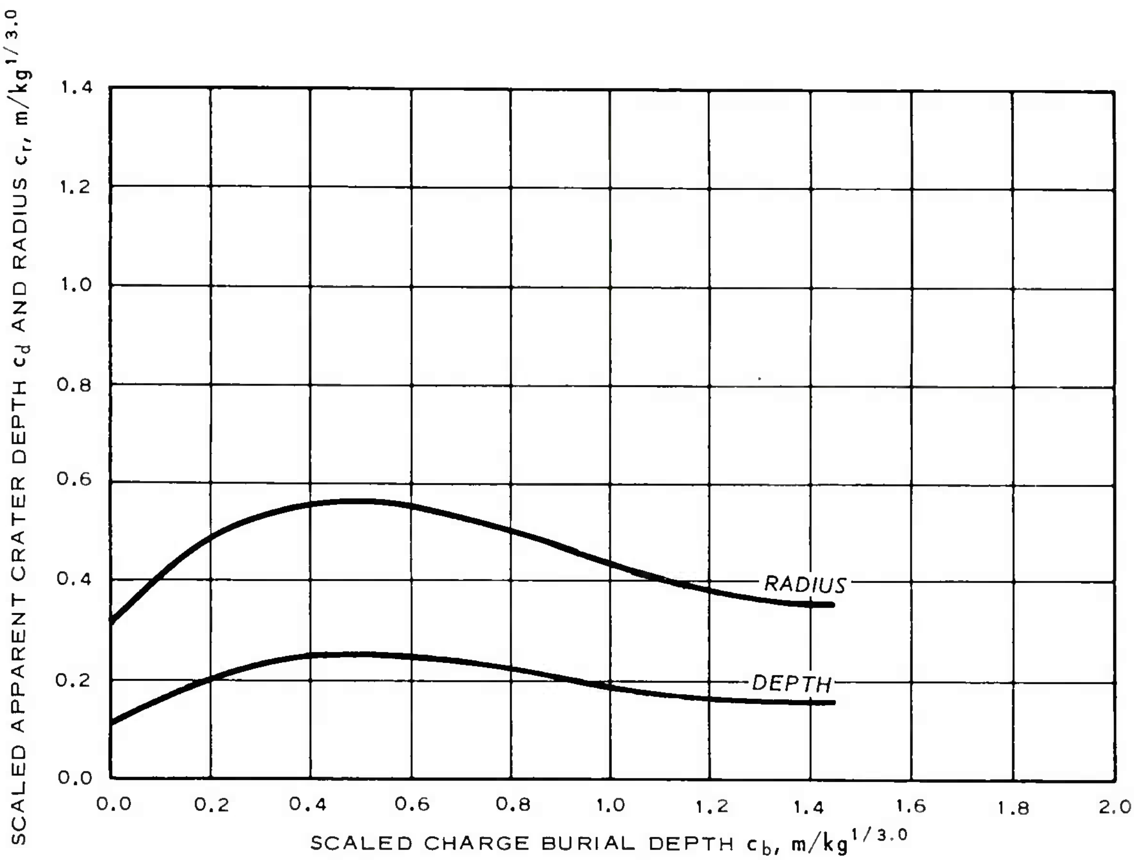
Figure 4. Scaled radius curve for a defined explosive and medium for which $a = 3.4$

Cratering Curves

14. Appendixes A and B list all high-explosive single-crater data available from the references listed in this report. A statistical regression analysis has been performed on the TNT data from these appendixes to produce data plots for nine media (Figures 5-13). There are two plots for each medium: (a) a scaled dimension plot (similar to that discussed in paragraph 13) on the left-hand page, and (b) a design chart on the right-hand page of the two-page spread for each medium. Each design chart graphically relates charge weights on the abscissa to crater dimensions and volumes on the ordinate; i.e., these charts solve Equations 5 and 6 graphically for the optimal cratering case. In the analysis of TNT data and the preparation of Figures 5-13, the following criteria were used:

a. The metric (SI) system of units was used, i.e., linear dimensions are expressed in metres, volumes in cubic metres, and charge weights in kilograms.

b. Data from different sites were grouped together if they represented similar media following the classification presented in Part I.

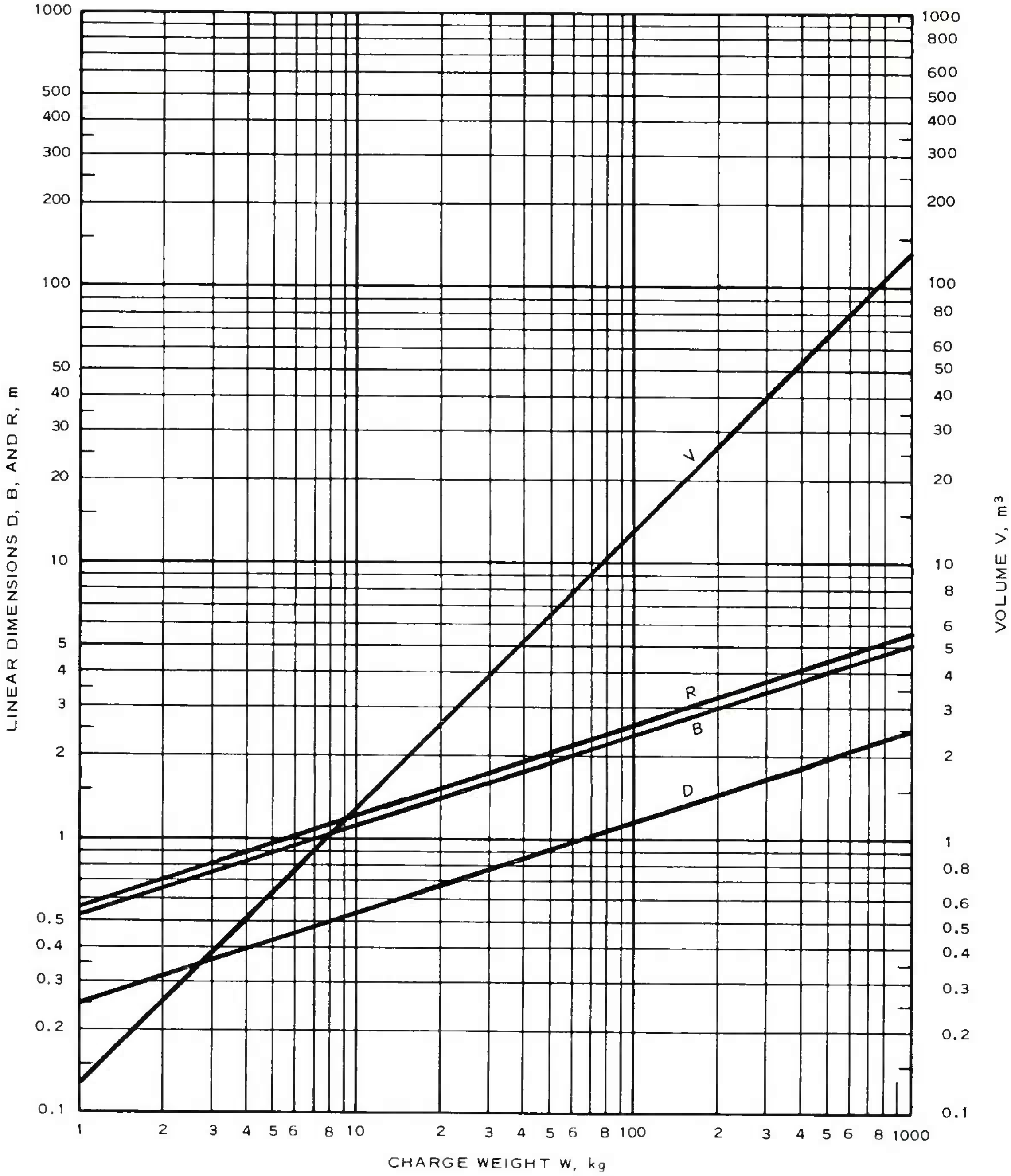


EQUATIONS

OPTIMUM BURIAL DEPTH	$B = 0.52W^{1/3.0}$
APPARENT RADIUS	$R = 0.56W^{1/3.0}$
APPARENT DEPTH	$D = 0.25W^{1/3.0}$
APPARENT VOLUME	$V = 0.13W$

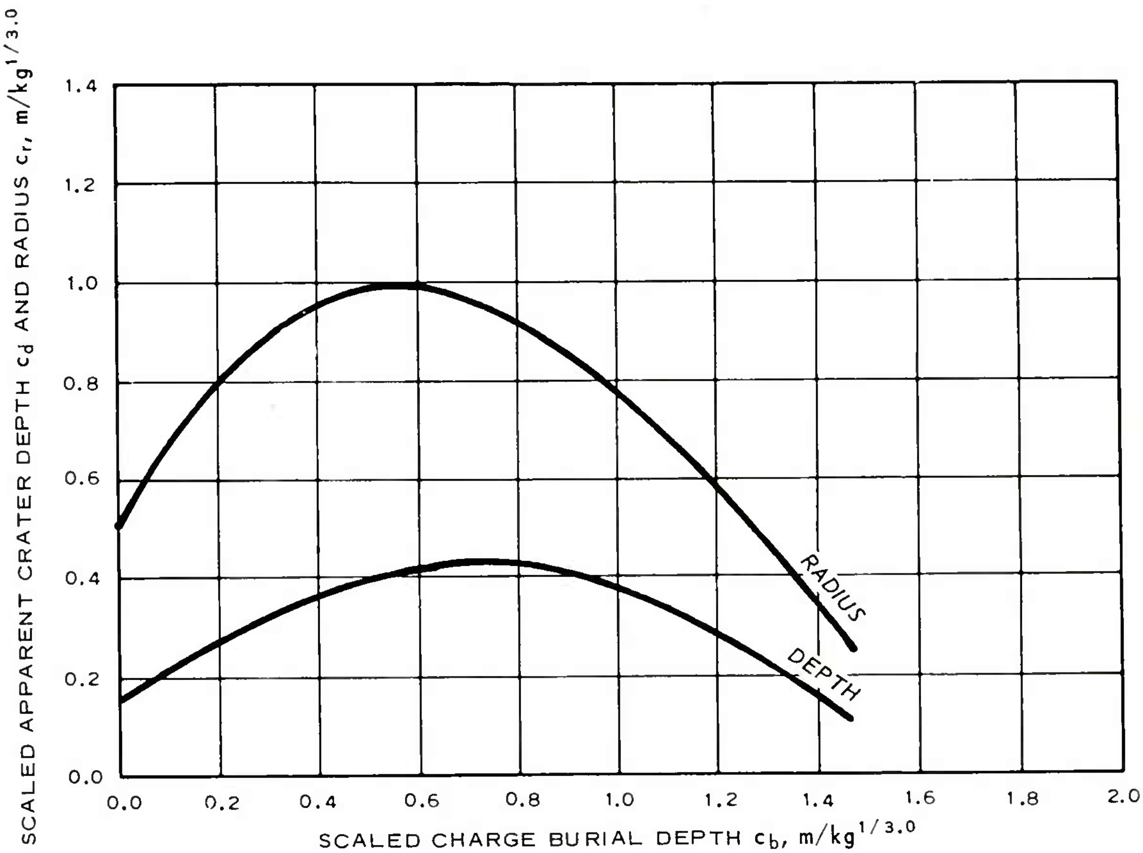
a. Scaled dimension curves

Figure 5. Scaled dimension curves and design chart for basalt, a high-strength rock (sheet 1 of 2)



b. Design chart

Figure 5 (sheet 2 of 2)

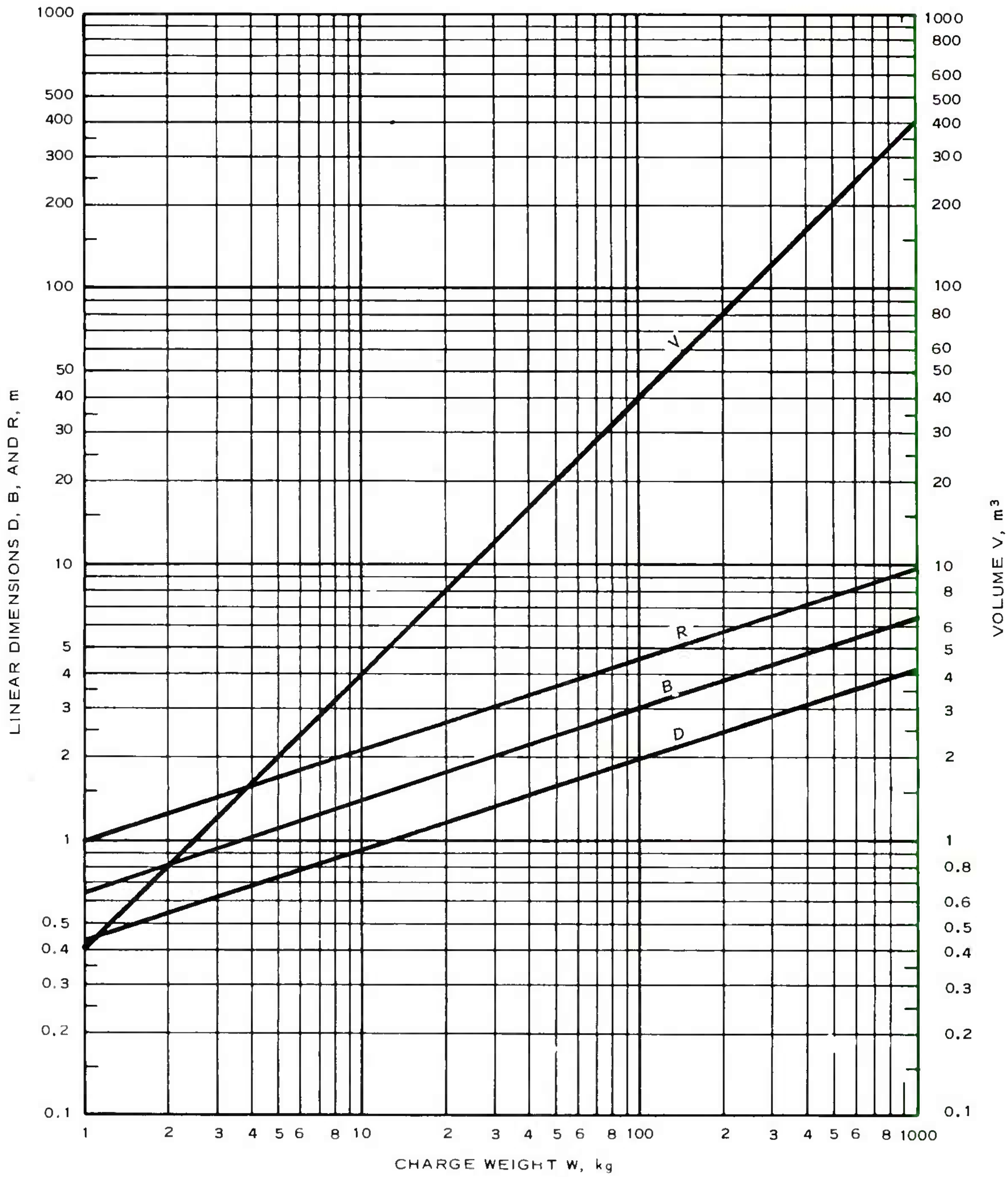


EQUATIONS

OPTIMUM BURIAL DEPTH	$B = 0.65W^{1/3.0}$
APPARENT RADIUS	$R = 0.97W^{1/3.0}$
APPARENT DEPTH	$D = 0.42W^{1/3.0}$
APPARENT VOLUME	$V = 0.40W$

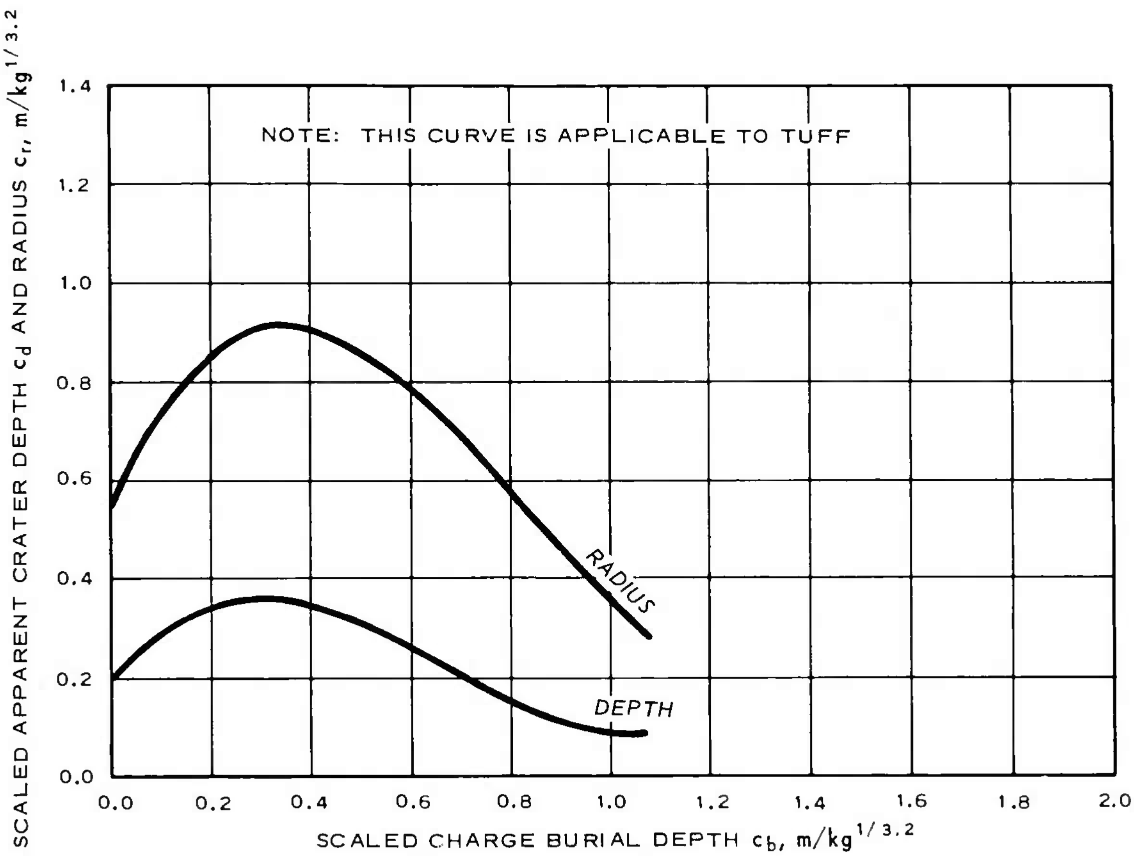
a. Scaled dimension curves

Figure 6. Scaled dimension curves and design chart for granite, a high-strength rock (sheet 1 of 2)



b. Design chart

Figure 6 (sheet 2 of 2)

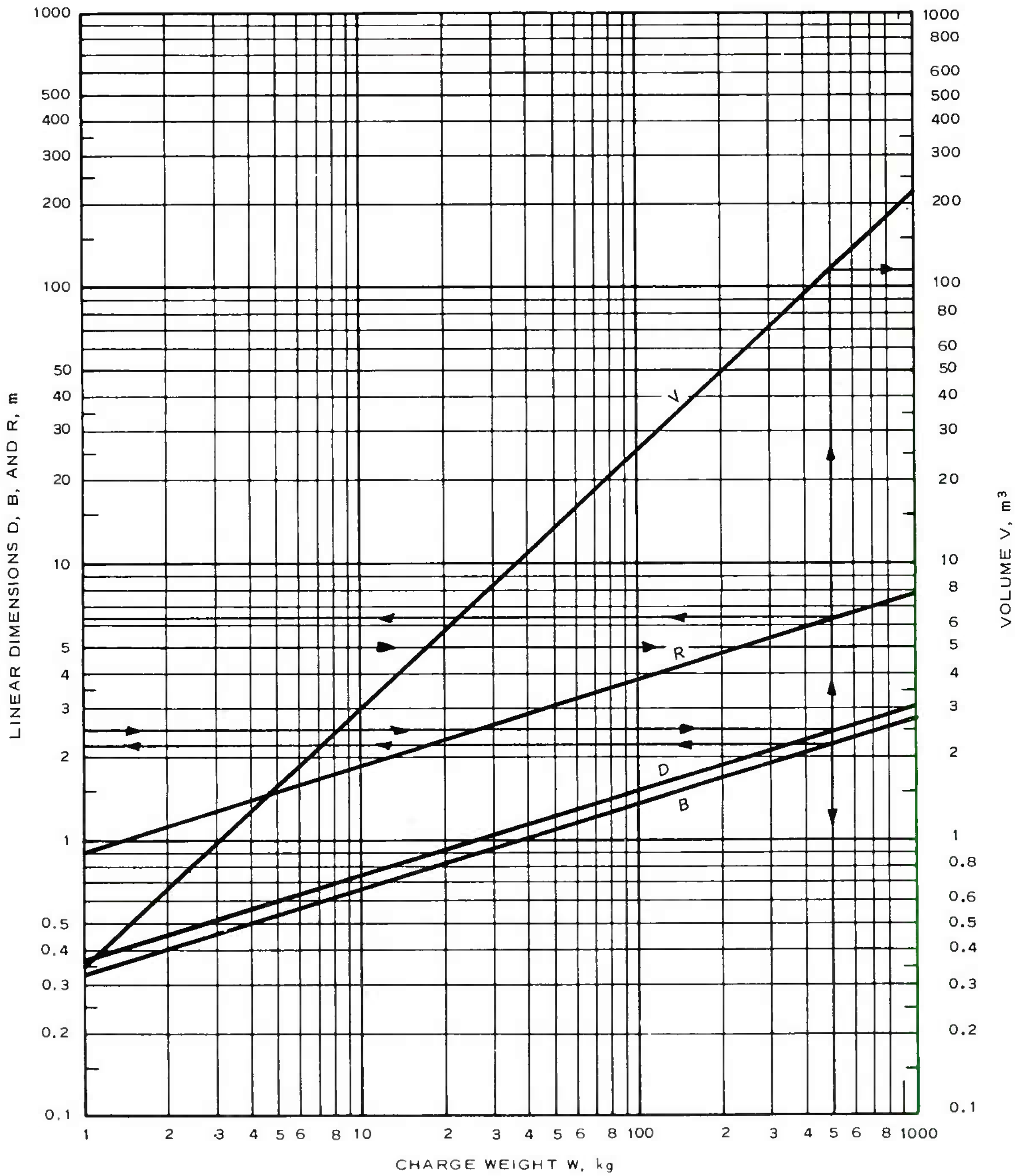


EQUATIONS

OPTIMUM BURIAL DEPTH	$B = 0.32W^{1/3.2}$
APPARENT RADIUS	$R = 0.91W^{1/3.2}$
APPARENT DEPTH	$D = 0.36W^{1/3.2}$
APPARENT VOLUME	$V = 0.34W^{3/3.2}$

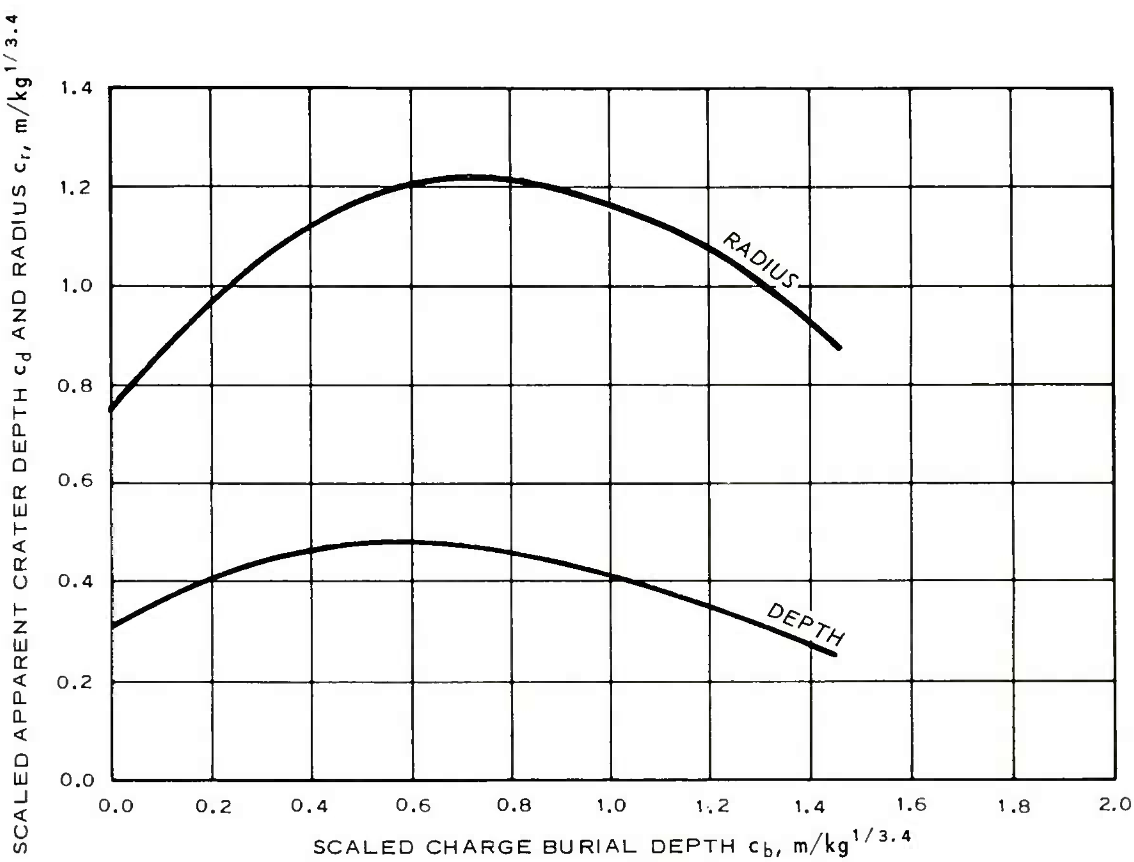
a. Scaled dimension curves

Figure 7. Scaled dimension curves and design chart for sandstone, an intermediate-strength rock (sheet 1 of 2)



b. Design chart

Figure 7 (sheet 2 of 2)

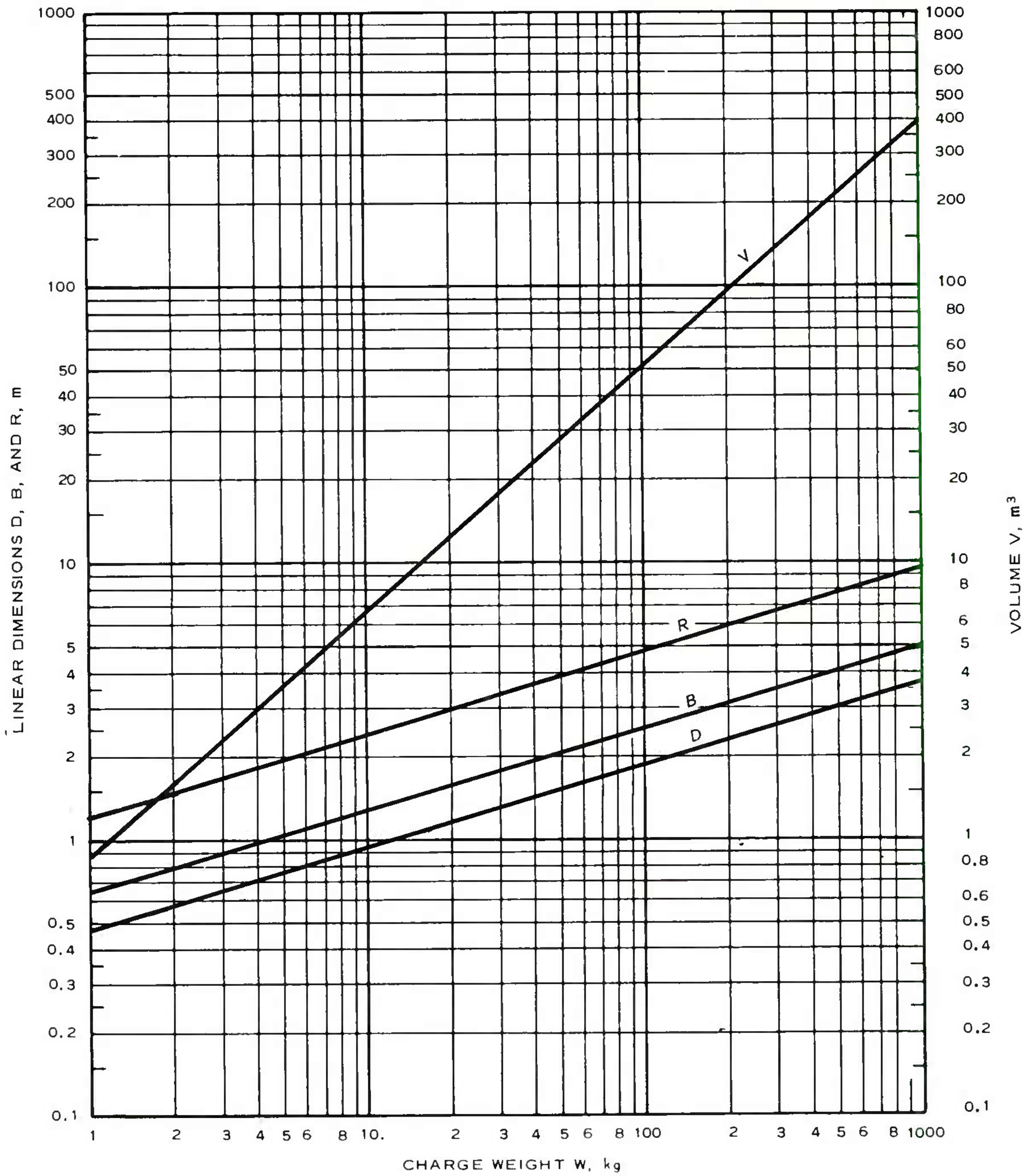


EQUATIONS

OPTIMUM BURIAL DEPTH	$B = 0.66W^{1/3.4}$
APPARENT RADIUS	$R = 1.22W^{1/3.4}$
APPARENT DEPTH	$D = 0.48W^{1/3.4}$
APPARENT VOLUME	$V = 0.89W^{3/3.4}$

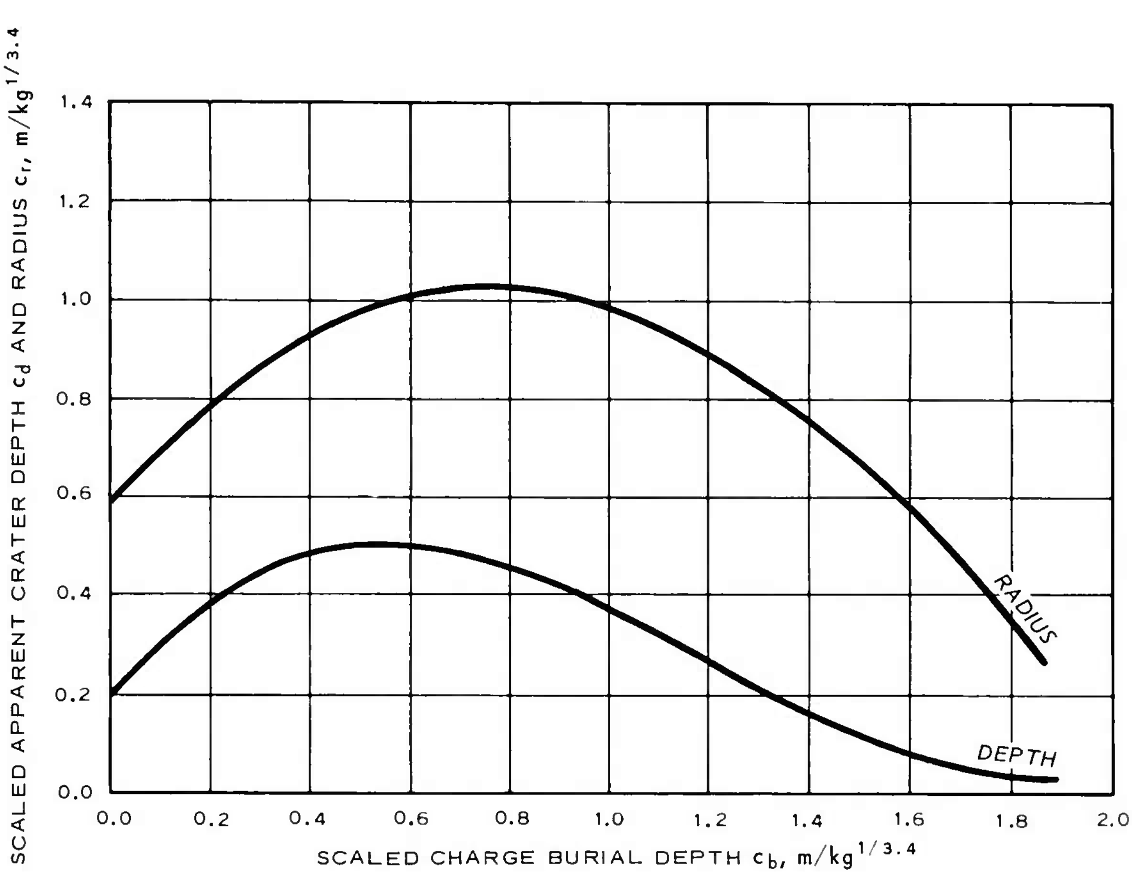
a. Scaled dimension curves

Figure 8. Scaled dimension curves and design chart for weak sandstones and shales, weak rocks (sheet 1 of 2)



b. Design chart

Figure 8 (sheet 2 of 2)

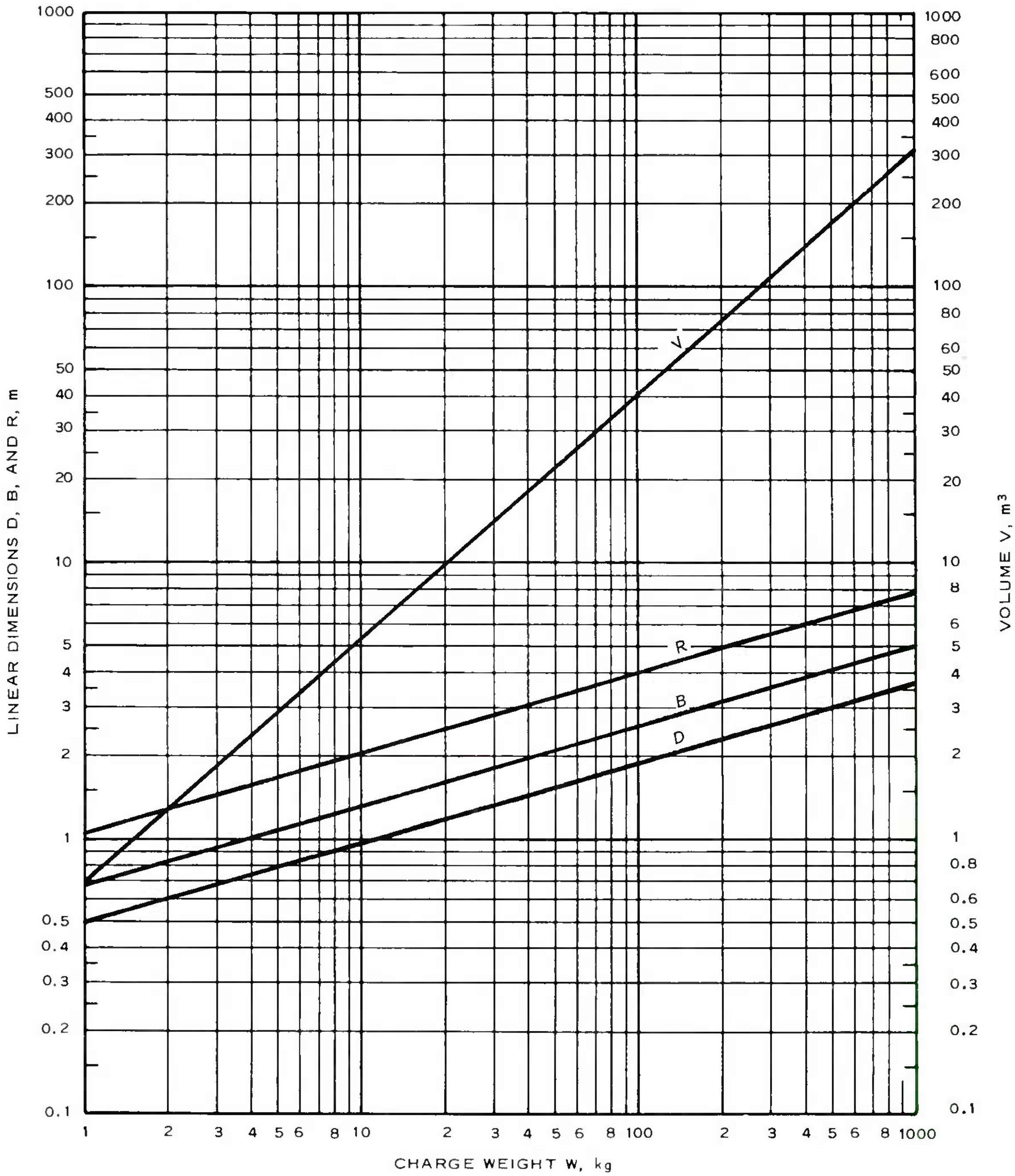


EQUATIONS

OPTIMUM BURIAL DEPTH	$B = 0.66W^{1/3.4}$
APPARENT RADIUS	$R = 1.02W^{1/3.4}$
APPARENT DEPTH	$D = 0.49W^{1/3.4}$
APPARENT VOLUME	$V = 0.69W^{3/3.4}$

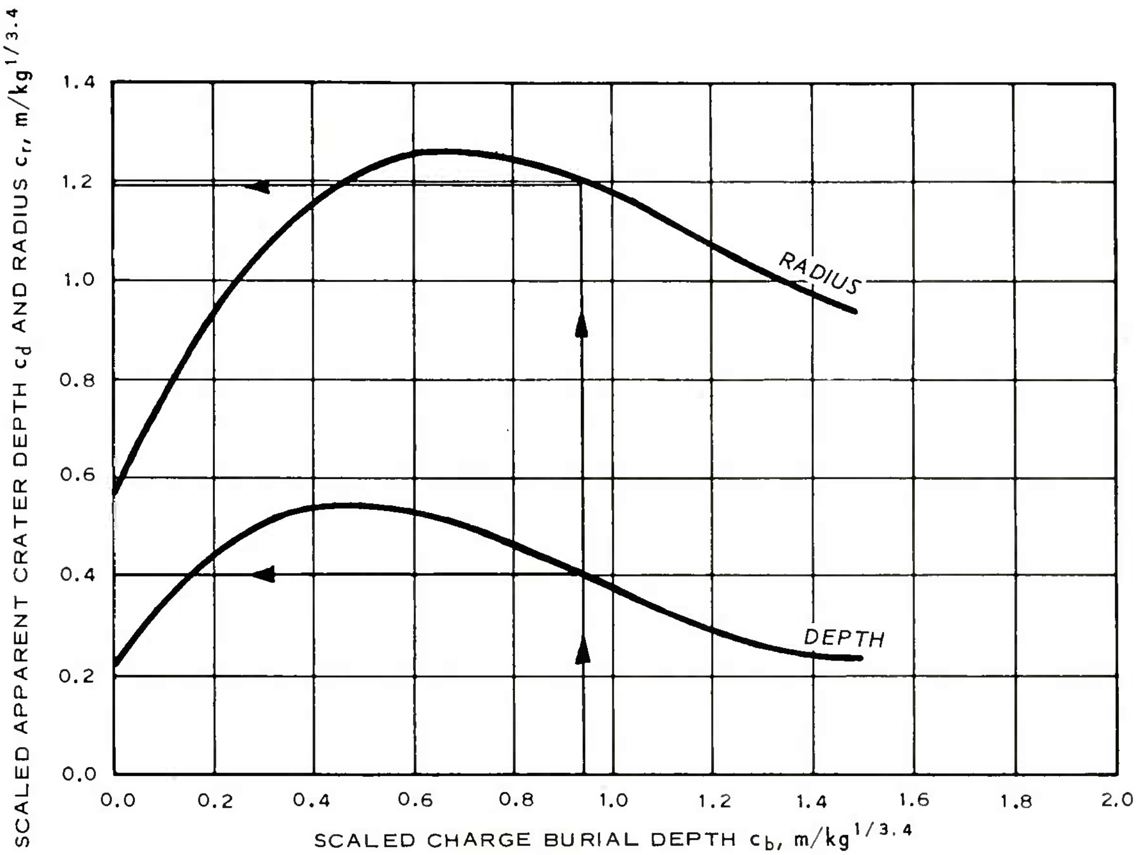
a. Scaled dimension curves

Figure 9. Scaled dimension curves and design chart for dry gravelly sand, a coarse-grained soil (GW) (sheet 1 of 2)



b. Design chart

Figure 9 (sheet 2 of 2)

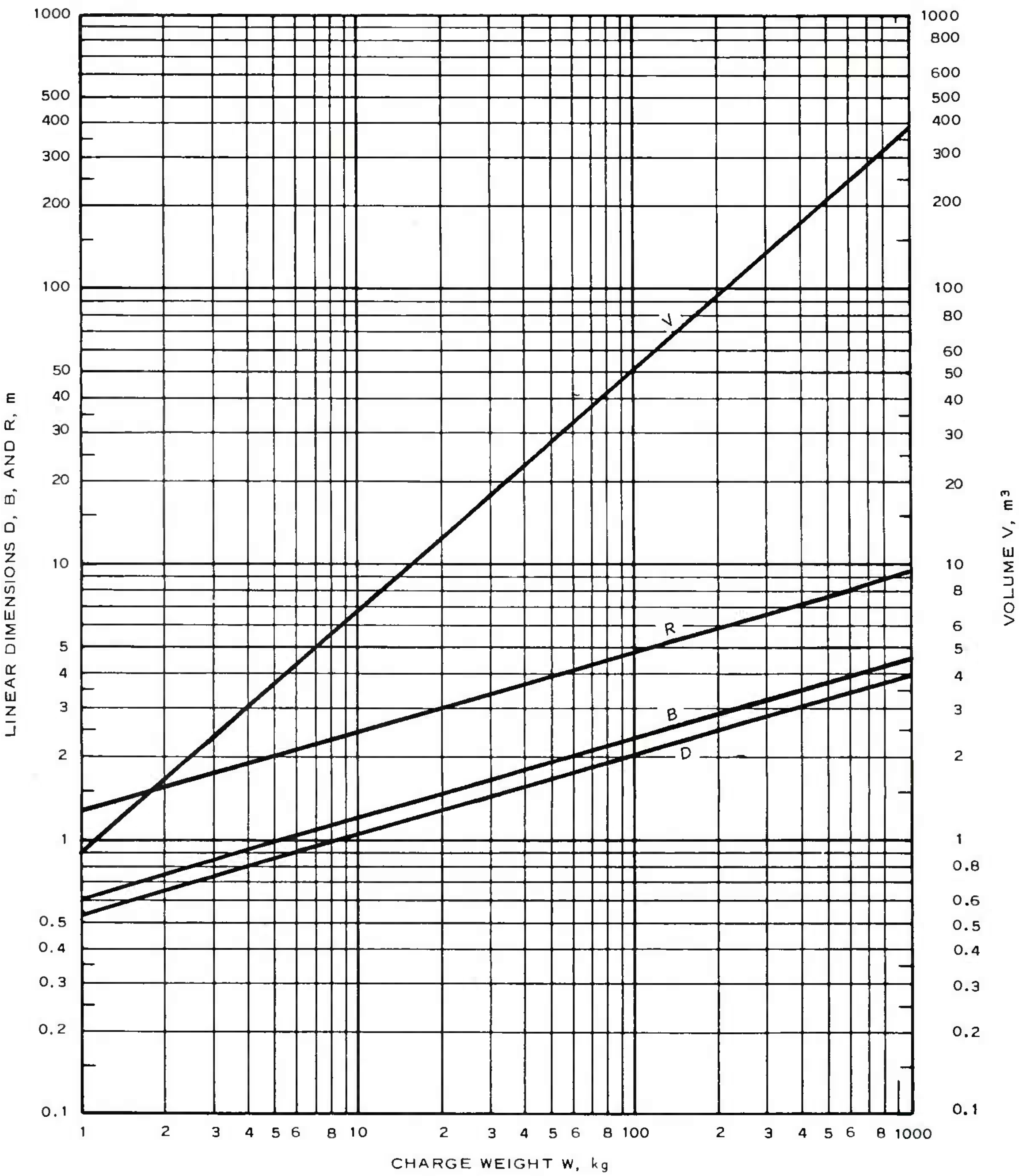


EQUATIONS

OPTIMUM BURIAL DEPTH	$B = 0.60W^{1/3.4}$
APPARENT RADIUS	$R = 1.25W^{1/3.4}$
APPARENT DEPTH	$D = 0.53W^{1/3.4}$
APPARENT VOLUME	$V = 0.89W^{3/3.4}$

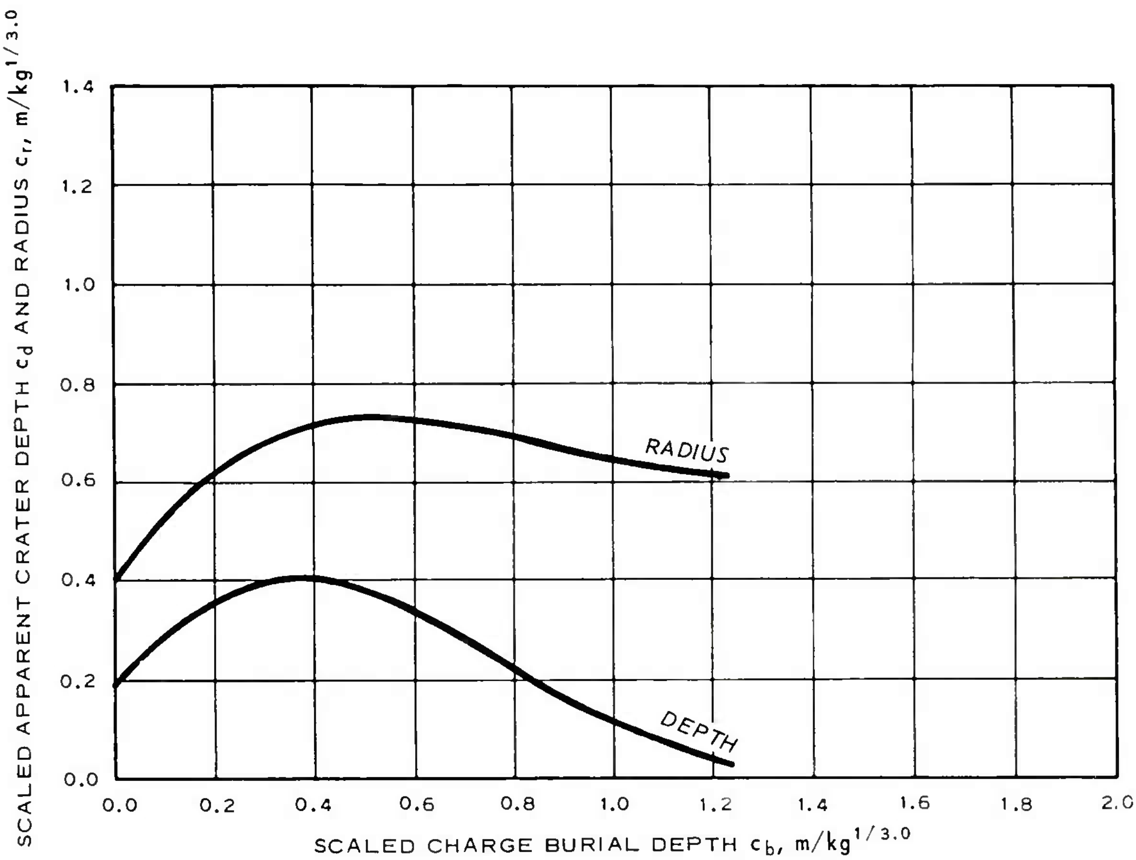
a. Scaled dimension curves

Figure 10. Scaled dimension curves and design chart for dry sand, a coarse-grained soil (sheet 1 of 2)



b. Design chart

Figure 10 (sheet 2 of 2)

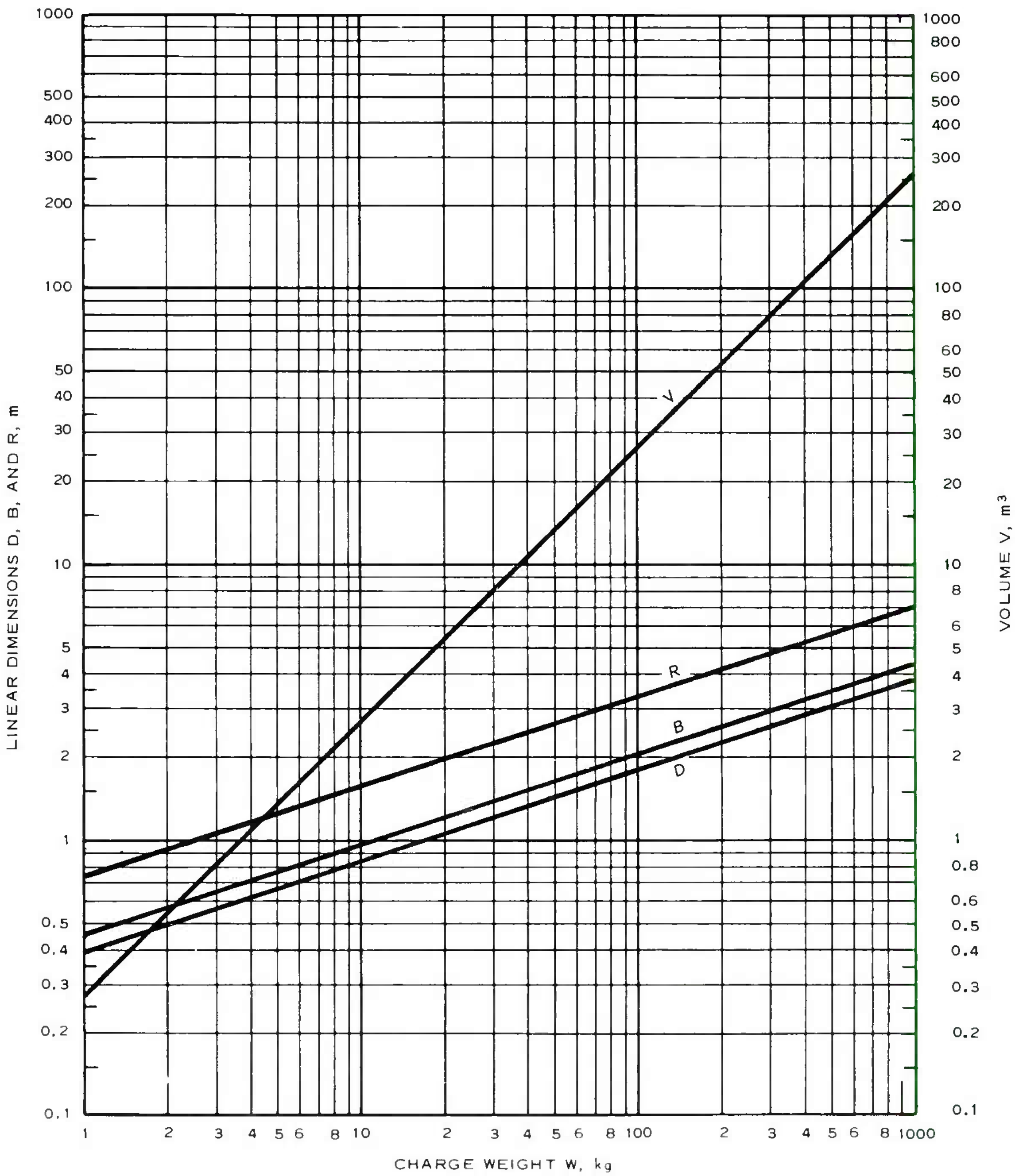


EQUATIONS

OPTIMUM BURIAL DEPTH	$B = 0.45W^{1/3.0}$
APPARENT RADIUS	$R = 0.73W^{1/3.0}$
APPARENT DEPTH	$D = 0.39W^{1/3.0}$
APPARENT VOLUME	$V = 0.27W$

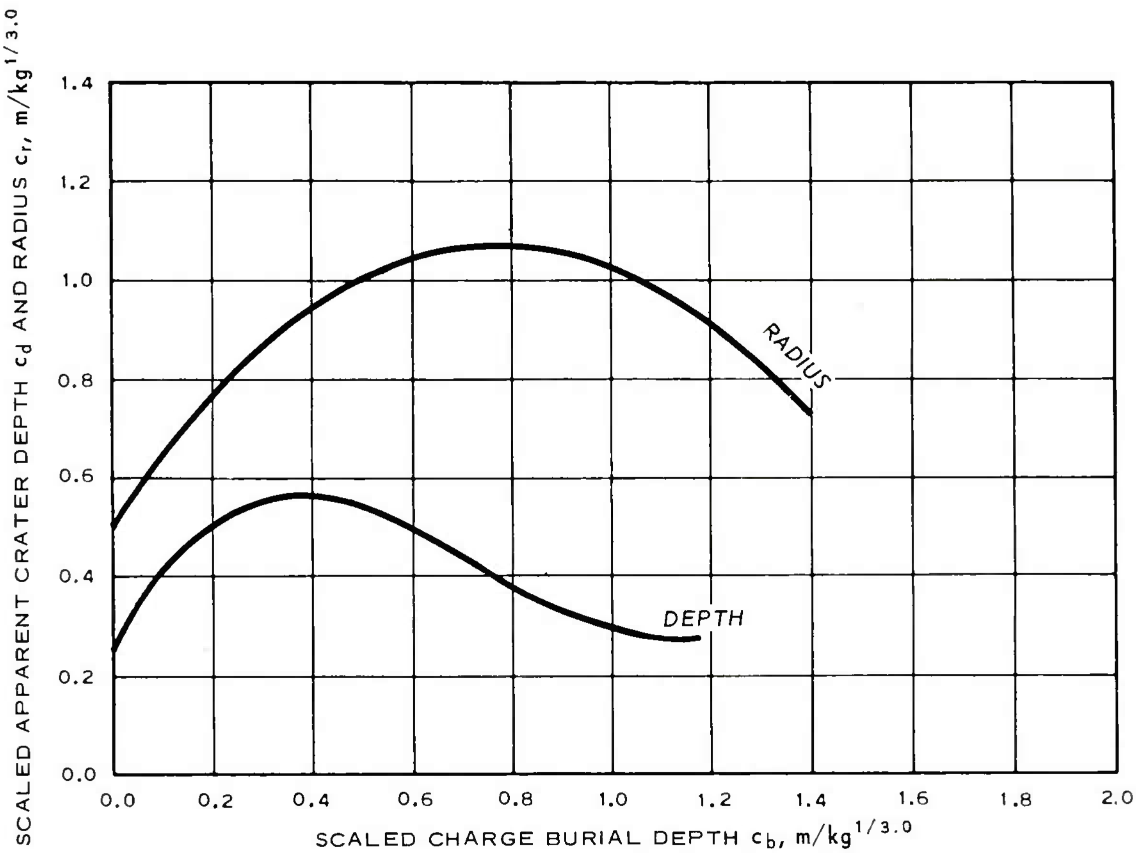
a. Scaled dimension curves

Figure 11. Scaled dimension curves and design chart for dry sandy clay, a coarse-grained soil (SC) (sheet 1 of 2)



b. Design chart

Figure 11 (sheet 2 of 2)

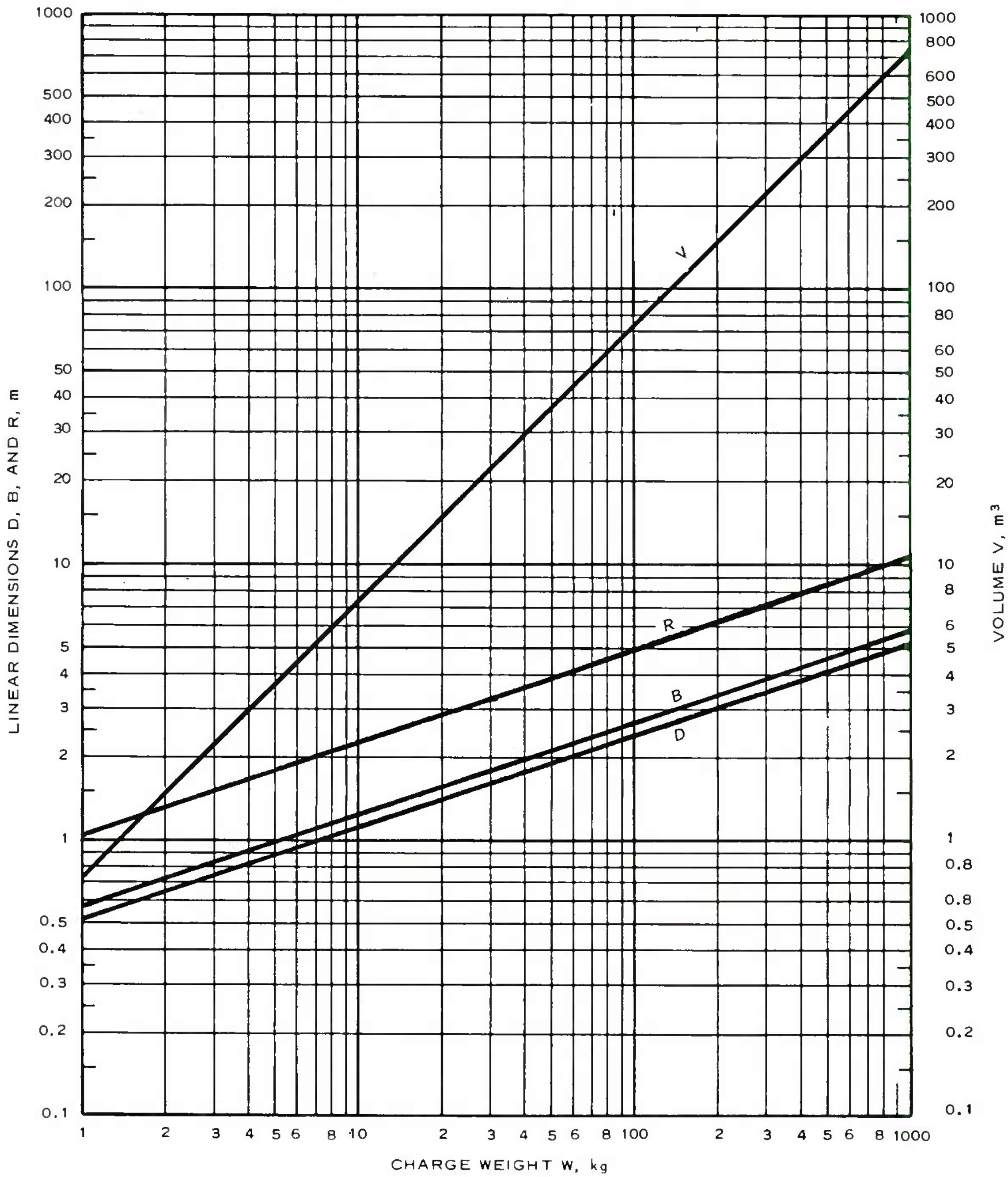


EQUATIONS

OPTIMUM BURIAL DEPTH	$B = 0.57W^{1/3.0}$
APPARENT RADIUS	$R = 1.03W^{1/3.0}$
APPARENT DEPTH	$D = 0.51W^{1/3.0}$
APPARENT VOLUME	$V = 0.72W$

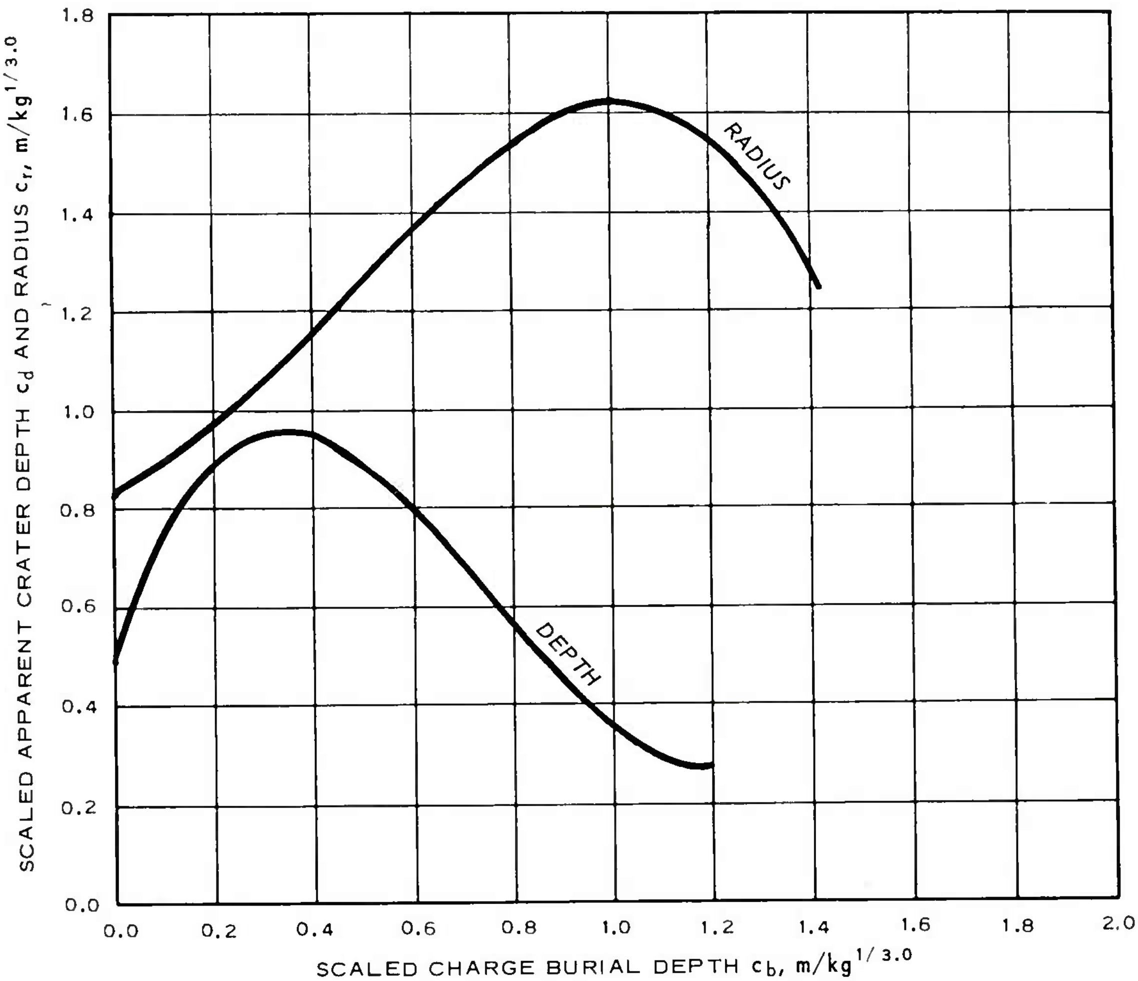
a. Scaled dimension curves

Figure 12. Scaled dimension curves and design chart for wet clay, a fine-grained soil (OH and MH) (sheet 1 of 2)



b. Design chart

Figure 12 (sheet 2 of 2)

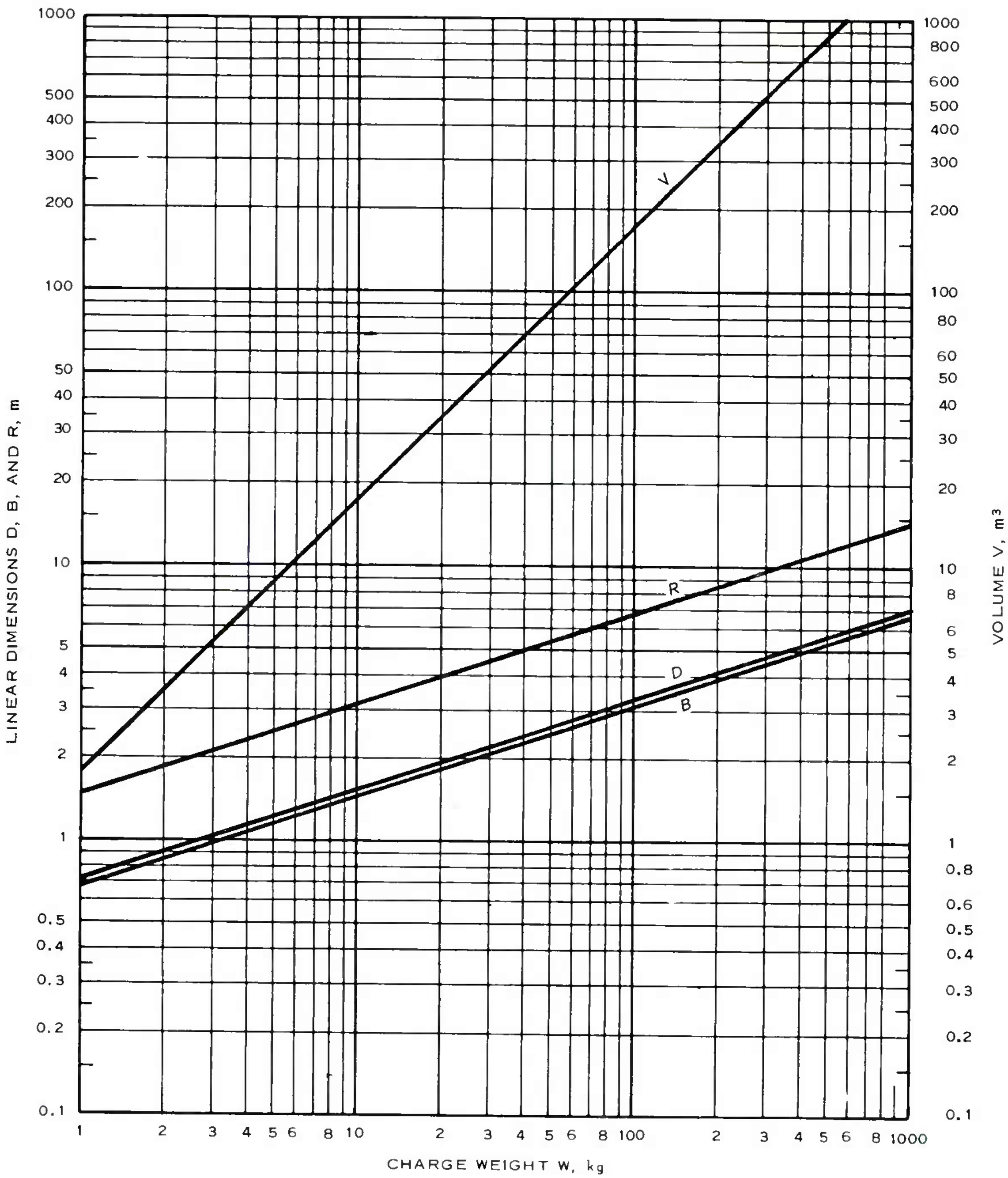


EQUATIONS

OPTIMUM BURIAL DEPTH	$B = 0.68W^{1/3.0}$
APPARENT RADIUS	$R = 1.45W^{1/3.0}$
APPARENT DEPTH	$D = 0.71W^{1/3.0}$
APPARENT VOLUME	$V = 1.77W$

a. Scaled dimension curves

Figure 13. Scaled dimension curves and design for saturated silty clay, a fine-grained soil (sheet 1 of 2)



b. Design chart

Figure 13 (sheet 2 of 2)

c. The third-order polynomial fit was chosen to represent the scaled dimension curves.

d. The least-squares method was used to fit the curves.

e. The value of a was assumed to be 3.0, 3.1, 3.2...3.6 for each medium, and that value that presented the smallest scatter between data point plots for all charge weights was chosen as the representative value for the considered medium.

f. In the preparation of the design charts, the optimum burial depth for each medium was considered to be the average of the optimum burial depths for crater radius and depth as determined from the peaks of the curves on the corresponding scaled dimension plot.

g. Scaled radius and scaled depth curves are presented in the same chart.

h. Only the parameter obtained from the scaled volume curve is presented, not the curve.

15. Table 3 summarizes the results obtained from the scaled dimension plots, and gives additional information regarding the data base used for the analysis of each medium. Necessary charge weights and burial depths and predicted crater dimensions may be calculated for the optimal cratering case in the various media by substitution of the values of appropriate exponents and coefficients from Table 3 into Equations 5 and 6.

Single-Crater Design Examples

Example 1

16. Problem. To predict the apparent crater radius and depth to be expected from the detonation of a single charge of 500 kg* of TNT at 6-m burial depth in dry sand.

17. Solution. The following parameters are given:

---

* A table of factors for converting metric (SI) units of measurement to U. S. customary units and U. S. customary units to metric (SI) units is given on page 3.

$$W = 500 \text{ kg}$$

$$B = 6.0 \text{ m}$$

$$a = 3.4 \text{ (Table 3)}$$

Using Equation 7, the scaled burial depth may be calculated:

$$c_b = \frac{B}{W^{1/a}} = \frac{6.0}{500^{1/3.4}} = 0.96$$

Entering the scaled dimension curve for dry sand (Figure 10a) with $c_b = 0.96$ gives the corresponding values of c_r and c_d

$$c_r = 1.19 \text{ m/kg}^{1/3.4} \quad \text{and} \quad c_d = 0.40 \text{ m/kg}^{1/3.4}$$

By Equation 5:

$$R = c_r W^{1/a} = 1.19 \times 500^{1/3.4} = 7.4 \text{ m}$$

$$D = c_d W^{1/a} = 0.40 \times 500^{1/3.4} = 2.5 \text{ m}$$

The resulting single crater will have a 7.4-m apparent radius and a 2.5-m apparent depth.

Example 2

18. Problem. To determine the single-charge weight of TNT and charge burial depth necessary to excavate a crater with an apparent radius of at least 5 m and an apparent depth of at least 2.5 m in sandstone.

19. Solution. The following parameters are given:

$$R \geq 5.0 \text{ m}$$

$$D \geq 2.5 \text{ m}$$

This problem can be solved using either mathematical procedures or the charts in Figures 5-13.

a. Mathematical.

From Table 3:

$$a = 3.2$$

$$c_b = 0.32$$

$$c_r = 0.91$$

$$c_d = 0.36$$

$$c_v = 0.34$$

From Equation 5a:

$$W = \left(\frac{R}{c_r}\right)^a = \left(\frac{5.0}{0.91}\right)^{3.2} = 233.22 \text{ kg}$$

$$W = \left(\frac{D}{c_d}\right)^a = \left(\frac{2.5}{0.36}\right)^{3.2} = 493.45 \text{ kg}$$

These calculations show that a charge of at least 493.45 kg of TNT will be necessary to achieve the required apparent depth of 2.5 m and that the required apparent radius of 5.0 m could be achieved with a 233.22-kg charge. To determine the apparent radius that will be obtained using 493.45 kg of TNT, use Equation 5:

$$R = c_r W^{1/a} = (0.91)(493.45)^{1/3.2} = 6.32 \text{ m}$$

Also from Equation 5, the required charge burial depth is

$$B = c_b W^{1/a} = (0.32)(493.45)^{1/3.2} = 2.22 \text{ m}$$

Using Equation 6, the apparent crater volume is

$$V = c_v W^{3/a} = (0.34)(493.45)^{3/3.2} = 113.87 \text{ m}^3$$

b. Graphic. Enter Figure 7b at $R = 5.0$ and read 233 kg on curve R. Enter Figure 7b at $D = 2.5$ and read ± 495 kg on curve D. The value ± 495 from curve D is larger than the value 233 from curve R; therefore, a

charge weight of 495 kg must be used. Read values of R, B, and V from the appropriate curves for a charge weight of 495 kg:

$$R = 6.3 \text{ m}$$

$$B = 2.2 \text{ m}$$

$$V = 113 \text{ m}^3$$

PART III: DITCHING DESIGNS

20. This part develops criteria for the design of ditches based upon the single-crater empirical scaling relationships discussed in Part II. The experimental data base for high-explosive ditching (Appendix C) is not as extensive as that for single craters, and is largely limited to row shots in soils. Thus, conclusions regarding row-crater effects are based largely upon a small number of simultaneously detonated high-explosive tests in soils.

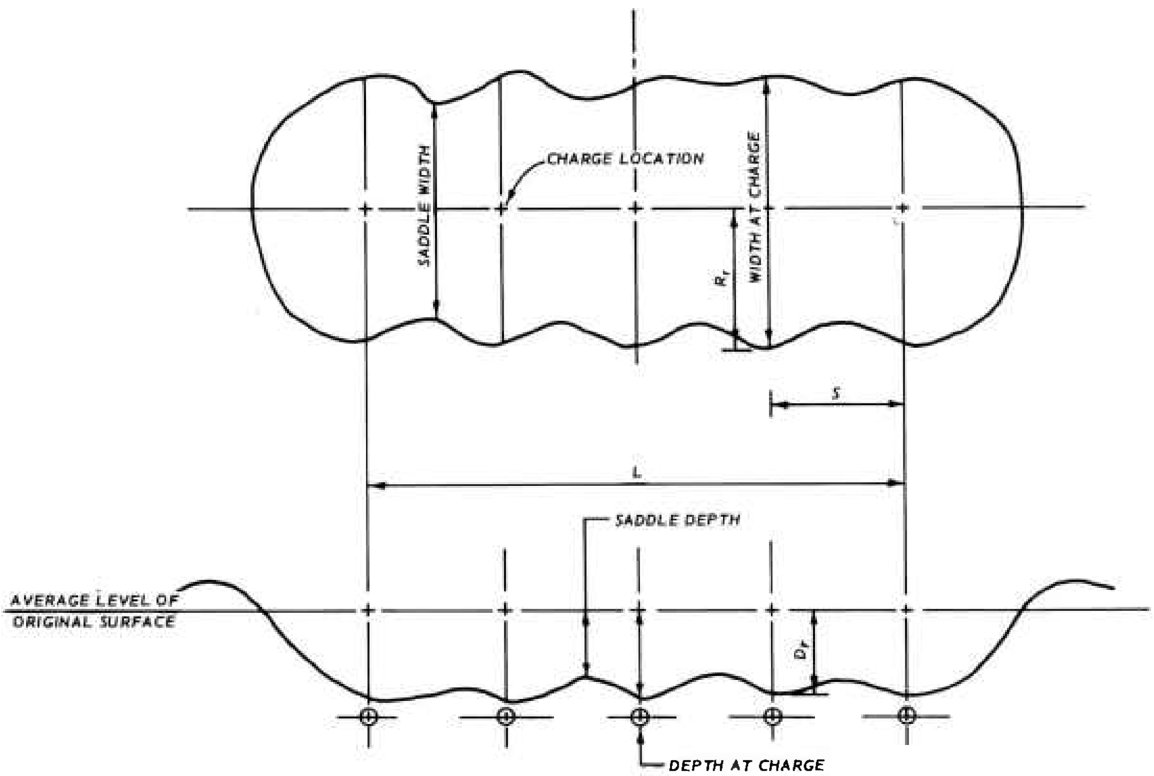
Ditch Smoothness

21. Criteria for ditch smoothness have been experimentally developed from row cratering in dry sandy clay.[25] Figure 14 shows a typical row crater with associated nomenclature and notation. It is apparent from this figure that ditch width and depth may vary, with the largest dimensions occurring close to the individual charge locations and the smallest dimensions occurring at "saddles" midway between the individual charge locations. If the spacing between charges S is sufficiently small, saddle dimensions will be approximately as large as near-charge dimensions, and a smooth ditch will be produced. However, it is also true that S must not be reduced any more than is necessary to obtain a smooth ditch, since production times and costs would be unnecessarily increased by closer-than-necessary spacings.

22. Figure 15 is a reprint of Figure 11 with experimentally developed row crater smoothness information superimposed. The curve labeled "Spacing Between Row Charges" represents c_s, the <u>scaled</u> upper limit for S where:

$$\frac{\text{Saddle width}}{\text{Width at charge}} \geq 0.95$$

$$\frac{\text{Saddle depth}}{\text{Depth at charge}} \geq 0.95$$



$$L = S(n-1) \qquad (11)$$

NOTE: R_r = AVERAGE APPARENT HALF-WIDTH OF ROW CRATER AT CHARGE LOCATIONS

D_r = MAXIMUM APPARENT DEPTH OF ROW CRATER

L = DITCH LENGTH FROM FIRST TO LAST CHARGE LOCATION

n = NUMBER OF CHARGES IN ROW

Figure 14. Plan and profile views of a five-charge row crater (n = 5)

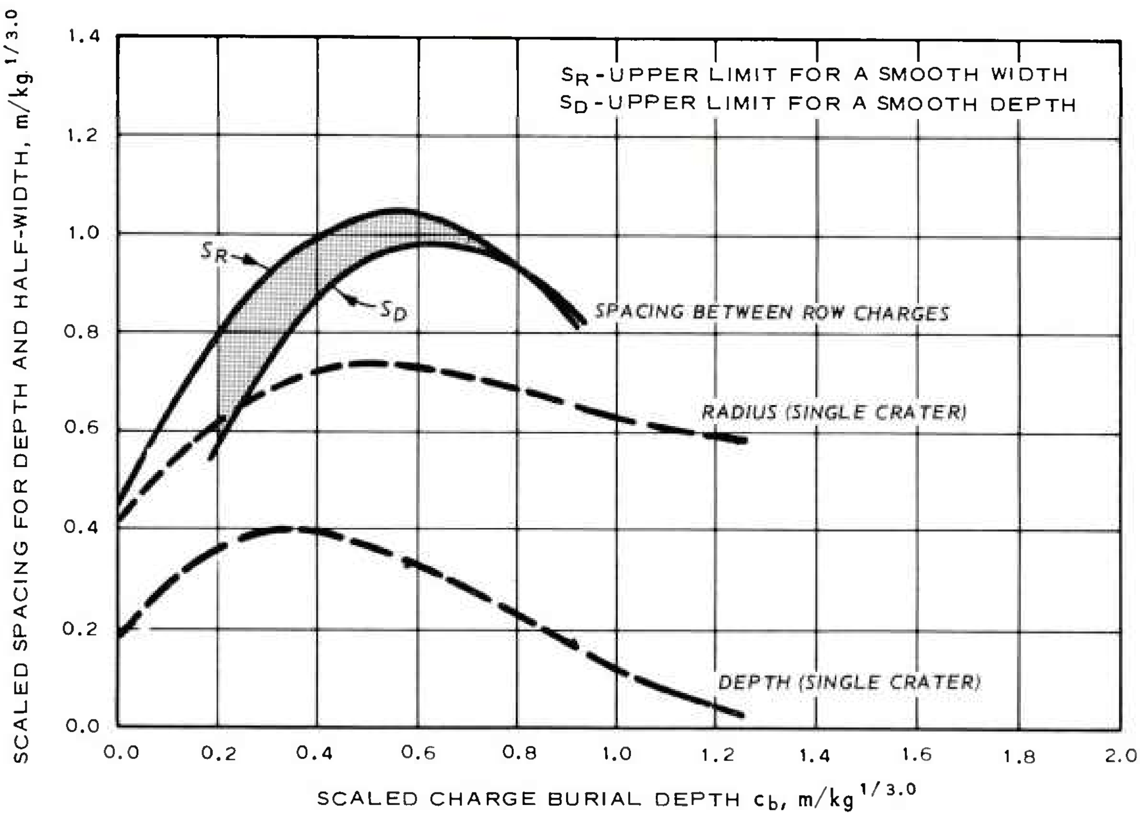


Figure 15. Scaled dimension curves for single and row craters for dry sandy clay, a coarse-grained soil (SC)

In other words, spacings S that correspond to values under this curve will yield smooth ditches, i.e., ditches within which widths and depths at the saddles are at least 95 percent as large as those at the charge locations. The shaded area just above this curve is a zone within which the ditches produced will maintain saddle widths of at least 95 percent of widths at charges, but which may have saddle depths as small as 60 percent of depths at charges.

23. From Table 3, scaled optimum burial depth c_b for dry sandy clay is 0.45. The ratio of the values of the scaled spacing between row charges c_s and the scaled apparent radius c_r at abscissa value $c_b = 0.45$ will give the spacing between row charges S in terms of the apparent radius R expected from a single charge emplaced at optimum burial depth in dry sandy clay:

$$\frac{S}{R} = \frac{c_s}{c_r} = \frac{0.90}{0.72} = 1.25$$

or

$$S = 1.25R \tag{12}$$

In the absence of comprehensive experimental data from other media, it is assumed that a smooth row crater from charges buried at optimum burial depth in any soil will require a spacing between row charges S of 1.25 times the apparent crater radius R that would be expected from a single charge emplaced at optimum burial depth for that medium. In actual practice with a variety of explosives in a variety of media, this relationship works well.

Ditching Design Example

24. Problem. A drainage ditch is to be excavated in wet clay on flat terrain. A minimum width of 8.0 m and a minimum depth of 1.5 m are required. Ditch length is to be 2000 m. Determine the amount of TNT required to produce the ditch with a single row of charges, and give the

charge size, burial depth, and spacing between charges to produce the ditch.

Given:

Required ditch width $2R_r \geq 8.0$ m

Required ditch depth $D_r \geq 1.5$ m

Required ditch length $L = 2000$ m

From Table 3:

$$a = 3.0$$

$$c_b = 0.57$$

$$c_r = 1.03$$

$$c_d = 0.51$$

The corresponding single crater will have:

$$R = R_r = 4.0 \text{ m}$$

$$D = D_r = 1.5 \text{ m}$$

Using Equation 5a the single charge may be calculated:

$$w = \left(\frac{R}{c_r}\right)^a = \left(\frac{4.0}{1.03}\right)^{3.0} = 58.57 \text{ kg}$$

and

$$w = \left(\frac{D}{c_d}\right)^a = \left(\frac{1.5}{0.51}\right)^{3.0} = 25.44 \text{ kg}$$

A charge of at least 58.57 kg of TNT will be necessary for each individual charge in the row shot to achieve the required ditch width $2R_r = 8.0$ m (the required ditch depth D_r could be achieved with 25.44-kg charges). To determine the apparent depth that will actually be achieved using 58.57 kg of TNT, use Equation 5:

$$D = c_d W^{1/a} = 0.51 \times 58.57^{1/3.0} = 1.98 \text{ m}$$

Also from Equation 5, required charge burial depth may be calculated:

$$B = c_b W^{1/a} = 0.57 \times 58.57^{1/3.0} = 2.21 \text{ m}$$

Spacing between charges (from paragraph 23):

$$S = 1.25R = 1.25 \times 4.00 = 5.00 \text{ m}$$

The length of this ditch will have a uniform cross section and is equal to the distance between the first and last charges. Using Equation 11 (Figure 14), the number of charges n may be calculated.

$$L = S(n - 1)$$

$$n = \left(\frac{L}{S}\right) + 1 \; \frac{2000}{5} + 1 = 401$$

Four hundred and one 58.57-kg charges will be required to excavate this ditch, or a total of 23,487 kg of TNT. The individual charges should be emplaced 2.21 m deep and spaced 5.00 m apart in the row.

PART IV: CONCLUSIONS

25. The large majority of data in the TNT cratering and ditching data base are from tests in dry soils although rock test sites are well represented in the data base. The weakest area is that for wet and saturated soils. TNT cratering data for saturated sand, though available in the data base, were inadequate for the analyses of this study.

26. The data base for cratering with single buried TNT charges is the most comprehensive available for any single explosive. It provides the best available basis for the comparison of cratering effects in differing media, and the standard for use in determining the cratering effectiveness of other explosives.

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Table 1

Media Classification for Explosive Excavation (from Reference 4)

Classification	Description
	Rock Type
Weak	Less than 27,580 kPa (4,000 psi) unconfined compressive strength
Intermediate-strength	Between 27,580 and 110,320 kPa (16,000 psi) unconfined compressive strength
High-strength	Greater than 110,320 kPa unconfined compressive strength
	Degree of Saturation or Water Content for Soils
Dry	Less than 50 percent saturated or less than 10 percent water content for soil or less than 3 percent water content for rock
Wet	Between 50 and 90 percent saturated or greater than 10 percent water content for soil or greater than 3 percent water content for rock
Saturated	Greater than 90 percent

Note: See Table 2 for a discussion of soil types.

Table 2

Summary of Unified Soil Classification System

(Adapted from Reference 6)

Major Divisions		Symbol	Soil Type
Coarse-grained soils	Gravel and Gravelly soils	GW	Well-graded gravels or gravel-sand mixtures, little or no fines
		GP	Poorly graded gravels or gravel-sand mixtures, little or no fines
		GM	Silty gravels, gravel-sand-silt mixtures
		GC	Clayey gravels, gravel-sands-clay mixtures
	Sand and Sandy soils	SW	Well-graded sands or gravelly sands, little or no fines
		SP	Poorly graded sands or gravelly sands, little or no fines
		SM	Silty sands, sand-silt mixtures
		SC	Clayey sands, sand-silt mixtures
Fine-grained soils	Silts and Clays Liquid limit < 50	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity
		CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
		OL	Organic silts and organic silt-clays of low plasticity
	Silts and Clays Liquid limit > 50	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
		CH	Inorganic clays or high plasticity, fat clays
		OH	Organic clays of medium to high plasticity, organic silts
Highly organic soils		PT	Peat and other highly organic soils

Note: Coarse-grained soils: Soils having 50 percent or less passing the No. 200 sieve. The coarse-grained soils include gravels, gravelly soils, sands, and sandy soils. The letter G is used to indicate a gravel, and the letter S is used to indicate sand. Gravel is material between 3 in. in diameter and the No. 4 (4.7 mm) sieve size, and sand is material between the No. 4 sieve size and the No. 200 (0.074 mm) sieve size. Particles larger than 3 in. in diameter are termed cobbles. Sand is divided into coarse, medium, and fine, the divisions being at the No. 10 and 40 sieve sizes.

Fine-grained soils: Soils having more than 50 percent passing the No. 200 sieve. The fine-grained soils are not divided according to grain size but according to plasticity and compressibility.

Table 3

Cratering Parameters for Optimum Burial Depth

Medium Name	a	Coefficient ($m/kg^{1/a}$) c_b	c_r	c_d	c_v	No. of Craters Used	Charge No. Used	Charge Minimum Weight kg	Charge Maximum Weight kg	Source
Basalt	3.0	0.52	0.56	0.25	0.13	34	8	3.6	18,143.7	9-11
Granite	3.0	0.65	0.97	0.42	0.40	11	2	145.1	1,161.2	12
Sandstone	3.2	0.32	0.91	0.36	0.34	33	11	3.6	145,149.6	13-15
Weak sandstones and shales	3.4	0.66	1.22	0.48	0.89	20	5	3.6	90.7	16
Dry gravelly sand	3.4	0.66	1.02	0.49	0.69	46	8	98.0	447,881.7	17-22
Dry sand	3.4	0.60	1.25	0.53	0.89	13	3	145.2	18,143.7	23
Dry sandy clay	3.0	0.45	0.72	0.39	0.27	89	9	29.0	145,149.6	17, 23-33
Wet clay	3.0	0.57	1.03	0.51	0.72	7	4	3.6	1,161.2	17, 23
Saturated silty clay	3.0	0.68	1.45	0.71	1.77	17	5	3.6	90.7	34

Note: For the completeness of the data list, those TNT cratering data not used in the statistical analysis are presented in Appendixes B and C and found in References 35-37.

APPENDIX A: CRATER DIMENSIONS FROM SINGLE HIGH-EXPLOSIVE CHARGE DETONATIONS IN ROCK

Table A1

Crater Dimensions from Single High-Explosive Charge Detonations in Rock

Series Name	Shot Designation	Sponsor	Date	Medium	Type of Explosive	Charge Weight lb	Charge Weight kg	Charge Burial Depth m	Apparent Crater Radius m	Apparent Crater Depth m	Apparent Crater Volume m^3	Source
Isthmian	1	Panama Canal	Nov 1946-	Basalt	TNT	8	3.63	0.91	0.98	0.33	1.00	11
Canal	2	Zone	Apr			75	34.02	1.22	1.06	0.21	0.98	
Study	3	Special	1947			75	34.02	1.83	2.11	1.05	5.98	
	4	Engineering				25	11.34	1.83	2.02	0.88	2.80	
	5*	Division				25	11.34	2.29	--	--	Mound	
	6					25	11.34	1.37	0.89	0.26	0.47	
	7					25	11.34	2.74	1.07	0.70	0.41	
	8					8	3.63	2.13	0.72	0.32	0.43	
	9					25	11.34	0.91	0.72	0.37	0.32	
	10					25	11.34	3.20	0.58	0.19	0.05	
	11*					75	34.02	3.81	--	--	Mound	
	12					200	90.72	3.66	2.90	1.21	15.49	
	13					25	11.34	0.46	1.40	0.93	2.42	
	14					25	11.34	0.00	0.61	0.22	0.16	
	15		Dec 1947- Mar 1948			200	90.72	0.00	1.42	0.49	1.40	
	16					200	90.72	0.00	1.62	0.37	1.78	
	17					200	90.72	0.37	1.69	0.40	1.22	
	18					200	90.72	0.37	1.13	0.34	0.85	
Isthmian	1	Panama Canal		Sandstone	TNT	25	11.34	2.27	0.33	0.12	0.27	15
Canal	2	Zone				8	3.63	0.91	1.17	0.53	1.12	
Study	3	Special				8	3.63	1.52	1.29	0.27	0,68	
	4	Engineering				75	34.02	3.66	0.16	0.30	0.02	
	5*	Division				8	3.63	2.13	--	--	Mound	
	6					75	34.02	1.22	2.56	1.37	12.14	
	7*					25	11.34	2.74	--	--	Mound	
	8*					25	11.34	3.20	--	--	Mound	
	9					25	11.34	0.46	1.57	0.68	2.50	
	10					200	90.72	3.54	1.51	0.37	5.36	
	11					8	3.63	0.30	1.06	0.39	0.70	
	12					25	11.34	1.83	1.42	0.42	2.22	
	13					25	11.34	1.37	0.91	0.43	1.71	
	14					25	11.34	0.91	1.50	0.40	1.29	
	15					25	11.34	0.00	1.05	0.26	0.54	
Isthmian	1	Panama Canal	Apr 1948	Cucaracha	TNT	25	11.34	2.29	1.91	0.46	3.46	16
Canal	2	Zone		formation		8	3.63	1.22	1.88	0.78	3.91	
Study	3	Special						0.91	1.79	0.73	1.08	
	4	Engineering						0.61	1.56	0.61	2.35	
	5	Division						2.13	1.26	0.37	0.80	
	6							1.53	1.52	0.52	2.16	
	7							0.30	1.22	0.56	1.33	
	8							1.83	1.86	0.87	5.15	
	9					25	11.34	0.46	1.94	0.81	4.76	
	10					25	11.34	1.37	2.90	0.99	11.54	
	11					200	90.72	3.66	3.94	1.31	35.48	
	12					75	34.02	3.66	3.03	0.72	13.61	
	13					25	11.34	0.00	1.12	0.55	1.10	
	14					50	22.68	0.00	2.29	0.94	6.69	
	15					50	22.68	0.00	2.68	1.16	--	
	16					50	22.68	0.18	2.21	0.79	4.97	
	1			Culebra	TNT	25	11.34	0.46	1.83	0.67	3.59	
	2			formation		25	11.34	1.37	2.99	1.39	16.16	
	3					8	3.63	1.52	1.47	0.48	1.57	
	4					25	11.34	0.00	1.30	0.46	1.07	
Dugway	501*	Department of		Limestone	TNT	320	145.10	2.01	3.41	2.77	33.98	12
(Under-	502*	Defense						0.76	2.53	1.19	7.99	
ground Ex-	601*			Granite				-0.76	0.37	0.05	--	
plosion Test	602							0.00	2.57	0.52	3.60	
Program)	603							0.76	2.96	0.79	7.42	
	604							1.52	4.42	1.52	31.43	
	605							3.81	5.21	1.86	52.67	
	606							7.62	1.58	0.61	1.65	
	607							0.76	4.39	1.62	32.28	
	608							0.76	4.27	1.40	26.82	
	609					2,560	1,161.20	1.52	7.68	3.11	192.55	
	610					2,560	1,161.20	1.52	7.04	2.65	138.19	
	611					320	145.10	0.76	4.08	1.52	26.45	
	612					320	145.10	5.18	4.02	2.32	39.64	
	801*	Department of		Sandstone	TNT	320	145.10	-0.76	--	--	--	13
	802	Defense				320	145.10	0.00	1.71	0.70	4.59	
	809					1,080	489.90	1.14	5.79	2.62	59.96	
	812					2,560	1,161.20	1.52	7.10	3.35	195.10	
	813					10,000	4,535.90	2.41	12.01	4.91	622.97	
	815					40,000	18,143.70	3.81	21.49	8.20	3,539.61	
	816					40,000	18,143.70	3.81	16.34	8.38	3,001.59	
	817					320,000	145,149.60	7.62	28.90	14.33	14,498.23	
	818					320	145.10	0.76	5.33	1.83	51.54	
	819							0.76	4.75	1.98	40.78	
	803		13 Nov 51					0.76	3.54	1.46	22.94	
	804		10 Oct 51					1.52	4.27	0.62	40.78	
	805*		6 Nov 51					3.81	2.83	4.54	33.70	
	807		15 Apr 52					0.76	4.36	1.55	41.34	
	808		3 May 52					0.76	3.99	1.77	45.87	

(Continued)

* Data not used in the statistical analysis.

Table A1 (Concluded)

Series Name	Shot Designation	Sponsor	Date	Medium	Type of Explosive	Charge Weight lb	Charge Weight kg	Burial Depth m	Apparent Crater Radius m	Apparent Crater Depth m	Apparent Crater Volume m^3	Source
Dugway (Continued)	810	Department of Defense	9 Apr 52	Sandstone	TNT	2,560	1,161.20	1.52	9.94	2.96	244.94	13
	811		30 Apr 52			2,560	1,161.20	1.52	7.65	3.20	199.63	
	814		4 Jun 52			40,000	18,143.70	3.81	17.22	8.20	3,058.22	
	806*		--			320	145.10	7.62	--	--	--	
Tuff	1	Sandia Laboratories	Spring 1959	Tuff	TNT	256	116.10	2.25	4.57	1.49	35.85	14
	2							2.93	4.24	1.28	31.15	
	6							2.11	3.57	1.31	16.74	
	7							3.16	2.10	0.70	3.17	
	11							2.84	3.54	0.55	10.11	
Buckboard	1*		23 Jun 60	Basalt (Nevada Test Site)	TNT	1,000	453.60	7.50	--	--	--	9
	2		21 Jun 60					5.76	1.41	0.43	1.27	
	3		30 Jun 60					4.48	4.77	1.58	50.97	
	4		16 Aug 60					2.93	5.09	1.98	74.19	
	5		1 Jul 60					1.46	4.57	2.29	53.52	
	6		27 Jun 60					7.32	1.86	1.58	5.24	
	7		30 Jun 60					5.67	3.25	1.16	18.52	
	8		24 Jun 60					4.48	5.16	2.68	99.11	
	9		16 Aug 60					2.93	3.70	1.46	22.65	
	10		6 Jul 60					1.46	4.82	2.13	75.32	
	11		14 Sep 60			40,000	18,143.70	7.77	13.61	7.59	1,535.34	
	12		27 Sep 60			40,000	18,143.70	13.01	17.37	10.58	3,822.77	
	13		24 Aug 60			40,000	18,143.70	17.92	11.22	4.94	656.95	
OSO	1*	Boeing Company	Aug 1963	Argillite	TNT	64	29.03	0.00	1.16	0.43	1.58	10
	2*					64	29.03	0.00	1.43	0.49	1.58	
Flat Top	I*	Defense Atomic Support Agency	22 Jun 64	Limestone	TNT	40,000	18,144.00	0.00	8.23	3.87	283.17	24
MTCE	S1 (C1)	Air Force Weapons Laboratory	21 Jun 65	Basalt	TNT	4,000	1,814.40	0.00	3.69	1.10	20.76	10
	S2a		17 Jun 65			4,000	1,814.40	0.00	3.26	1.22	19.03	
	S3a		16 Jul 65			4,000	1,814.40	0.00	3.47	1.22	24.15	
	S4a		10 Jul 65			4,000	1,814.40	0.00	3.17	1.22	17.13	
	LS		8 Jul 65			16,000	7,257.60	0.00	5.70	1.71	103.61	
	C2		25 Jun 63	Basalt (Yamike Firing Center)	TNT	4,000	1,814.40	0.67	4.27	1.62	42.48	
	St 1*		11 Jun 65			4,000	1,814.40	-0.67	1.13	0.40	1.05	
	St 2a*		14 Jul 65			4,000	1,814.40	-0.67	2.07	0.58	3.94	
	St 3a*		23 Jun 65			4,000	1,814.40	-0.67	1.37	0.37	0.71	

* Data not used in the statistical analysis.

APPENDIX B: CRATER DIMENSIONS FROM SINGLE HIGH-EXPLOSIVE CHARGE DETONATIONS IN SOIL

Table B1

Crater Dimensions from Single High-Explosive Charge Detonations in Soil

						Charge			Apparent Crater			
Series Name	Shot Designation	Sponsor	Date	Medium	Type of Explosive	Weight lb	Weight kg	Burial Depth m	Radius m	Depth m	Volume m^3	Source
Isthmian	1	Panama Canal	1948	Marine muck	TNT	8	3.63	0.30	1.59	1.30	6.57	34
Canal	2	Zone				8	3.63	0.91	2.01	1.55	7.29	
Study	3	Special				8	3.63	1.52	2.71	0.49	4.62	
	4	Engineering				8	3.63	2.13	1.38	0.96	3.91	
	5	Division				25	11.34	0.46	2.70	2.03	19.89	
	6							0.91	2.77	2.01	24.82	
	7							1.37	2.36	1.89	20.90	
	8							1.83	1.99	1.84	16.25	
	9							2.29	3.34	0.91	12.62	
	10							2.74	3.61	0.60	11.38	
	11							3.20	3.43	0.89	8.25	
	12					75	34.02	1.22	3.83	2.83	57.53	
	13					75	34.02	3.66	5.95	0.80	37.21	
	14*					200	90.72	3.66	10.09	0.76	96.43	
	15					25	11.34	0.00	1.73	1.18	6.15	
	16(1A)					50	22.68	0.00	2.19	1.52	13.69	
	17(2A)					50	22.68	0.00	2.33	1.52	13.00	
Isthmian	1	Panama Canal		Residual	TNT	25	11.34	0.46	1.43	0.90	2.65	35
Canal	2	Zone		clay (wet)		75	34.02	3.66	3.76	0.59	10.59	
Study	3	Special				8	3.63	1.52	1.33	0.51	1.38	
	4	Engineering				75	34.02	2.44	3.34	1.52	21.17	
	5	Division				200	90.72	1.83	5.16	2.87	100.49	
	6					25	11.34	0.00	1.16	0.64	0.93	
	7					25	11.34	1.37	2.21	0.97	6.03	
	8					8	3.63	2.13	1.07	0.76	1.59	
Jangle - HE	HE-1	Department of	25 Aug 51	Alluvium	TNT	2,560	1,161.20	0.62	5.64	2.04	56.92	18
	HE-2	Defense/	03 Sep 51	(Nevada		40,000	18,143.70	1.56	11.89	4.57	991.09	
	HE-3	Stanford	15 Sep 51	Test Site		2,560	1,161.20	2.08	6.18	3.29	169.90	
	HE-4*	Research	9 Sep 51	Area 10)				-0.62	2.10	0.58	3.11	
	HE-5	Institute	31 Sep 51					1.25	5.91	2.29	113.27	
	HE-6		2 Oct 51					0.92	6.04	1.86	101.94	
	HE-7		4 Oct 51					0.79	5.79	2.04	93.45	
	HE-8*		13 Oct 51			216	98.00	0.33	Not measured			
	8-A*				Pentolite	177	80.10	0.33	2.76	1.04	7.67	
	HE-9		14 Oct 51		TNT	216	98.00	0.26	2.53	1.22	7.65	
	9-A*				Pentolite	177	80.10	0.26	2.67	1.07	7.22	
	HE-10		14 Oct 51		TNT	216	98.00	0.91	3.44	1.68	24.35	
	10-A*				Pentolite	177	80.10	0.91	3.09	1.52	14.16	
Dugway	301*	Department of		Dry clay	TNT	320	145.15	-1.07	0.76	0.30	--	23
	302	Defense	29 Mar 51	(Utah)				0.00	2.21	1.22	6.80	
	303		2 Apr 51					0.40	2.74	1.68	16.99	
	304		4 Apr 51					1.07	3.20	1.83	23.22	
	305		6 Apr 51					2.13	3.58	2.13	36.81	
	306		12 Apr 51					4.27	4.57	0.30	6.68	
	307		10 Apr 51					6.40	3.05	0.30	2.83	
	308		16 Apr 51			2,560	1,161.22	7.90	6.10	3.66	152.91	
	309		18 Apr 51			2,560	1,161.22	2.13	6.55	4.72	206.71	
	310		23 Apr 51			320	145.15	1.07	3.35	2.13	25.49	
	312		4 May 51			2,560	1,161.22	2.13	7.92	4.57	368.12	
	315		10 May 51			40,000	18,143.70	5.33	19.51	12.80	5,380.20	
	318					320,000	145,149.60	10.67	36.58	18.29	31,148.55	
	311					8	3.63	0.61	1.22	0.76	1.87	
	314					8	3.63	0.76	1.37	0.91	2.44	
	316					110	49.90	0.75	2.74	1.83	20.95	
	313					320	145.15	1.07	3.89	2.44	42.48	
	317					2,560	1,161.22	2.13	7.01	4.72	311.49	
	319					2,560	1.161.22	2.13	7.01	4.11	220.87	
	Symmetry					320	145.15	2.13	3.81	2.13	36.81	
Dugway	101*	Department of	7 Jun 51	Dry sand	TNT	320	145.15	-1.25	0.15	0.02	--	23
	102	Defense	7 Jun 51					0.00	2.33	0.76	7.08	
	103		7 Jun 51					0.40	3.32	1.83	20.39	
	104		7 Jun 51					1.07	3.66	1.98	36.81	
	105		19 Jun 51					2.13	4.72	2.59	73.62	
	106		27 Jun 51					4.27	5.11	1.37	31.15	
	107		27 Jun 51					6.40	4.11	1.07	22.37	
	108		10 Jul 51			2,560	1,161.22	0.79	5.79	2.97	147.25	
	109		10 Jul 51			2,560	1,161.22	2.13	7.54	2.59	232.20	
	110		13 Aug 51			320	145.15	1.07	3.96	2.29	45.31	
	112		27 Jul 51			2,560	1,161.22	2.13	9.14	3.67	368.12	
	115		8 Aug 51			40,000	18,143.70	5.33	22.86	7.01	5,097.03	
	111*					8	3.63	0.76	1.83	1.22	3.96	
	113					320	145.15	1.07	4.27	2.06	53.80	
	114*					8	3.63	0.76	1.83	1.07	4.25	
	116					320	145.15	2.67	5.64	2.74	99.11	
	0.029A-15*					8	3.63	0.76	---	---	---	
	0.04A-16*					20	9.07	0.76	--	--	--	
	0.05A-17*					40	18.14	0.76	--	--	--	
Dugway	402	Department of	23 Aug 51	Wet clay	TNT	320	145.15	0.76	5.72	3.05	116.10	23
	403	Defense	11 Aug 51	(Utah)		2,560	1,161.22	1.52	12.73	3.89	821.19	
	401					8	3.63	0.76	2.13	1.52	8.78	
	405					8	3.63	0.76	1.83	1.25	7.65	
	404		21 Aug 51			320	145.15	0.76	5.33	3.51	110.44	

(Continued)

* Data not used in the statistical anlaysis.

Table B1 (Continued)

Series Name	Shot Designation	Sponsor	Date	Medium	Type of Explosive	Charge Weight lb	Charge Weight kg	Burial Depth m	Apparent Crater Radius m	Apparent Crater Depth m	Apparent Crater Volume m^3	Source
Mole	101	Armed Forces	28 Jun 52	Dry clay	TNT	256	116.12	1.94	3.22	1.65	21.02	17
	102	Special		(Utah)				0.97	3.12	1.95	22.95	
	102A	Weapons	6 Jul 52					0.97	2.93	1.63	16.66	
	105	Project/	13 Jun 52					1.94	3.29	1.77	24.26	
	106	Stanford	19 Jul 52					0.50	2.77	1.89	15.24	
	107	Research	20 Aug 52					0.00	2.01	1.19	6.57	
	311	Institute	20 Oct 53	Moist clay	TNT			0.97	4.72	3.41	89.13	
	312		22 Oct 53	(Califor- nia)				0.97	5.33	2.77	94.73	
Mole	301*	Armed Forces	15 Sep 53	Wet sand	TNT	256	116.12	--	--	--	--	17
	302	Special	18 Sep 53					0.97	6.10	1.89	95.92	
	304	Weapons	23 Sep 53					1.45	5.94	2.01	--	
	305	Project/	26 Sep 53					0.50	4.91	1.92	58.62	
	306	Stanford	8 Oct 53					0.25	3.99	1.16	38.94	
	307	Research	8 Oct 53					0.00	3.93	1.43	37.30	
	308*	Institute	10 Oct 53					-0.25	2.71	1.22	12.70	
	309		16 Oct 53					0.97	5.09	1.86	76.98	
	310		17 Oct 53					0.97	5.33	1.58	73.57	
Mole	202	Armed Forces	14 Sep 52	Alluvium	TNT	256	116.10	1.94	3.44	1.68	29.59	17
	203	Special	19 Sep 52	(Nevada				0.97	2.55	1.20	10.07	
	204	Weapons	4 Oct 52	Test Site				0.50	2.88	0.79	10.30	
	205	Project/	8 Oct 52	Area 10)				0.25	2.76	0.62	8.49	
	206	Stanford	11 Oct 52					0.00	1.94	0.52	3.66	
	207*	Research	15 Oct 52					-0.25	1.23	0.43	1.06	
	212	Institute	24 Oct 52					1.94	3.57	1.78	34.18	
	401		23 Oct 54					0.97	3.23	1.68	23.34	
	402		26 Oct 54					1.45	3.37	1.89	26.69	
	403		28 Oct 54					0.25	2.53	1.04	8.31	
	404		30 Oct 54					1.94	3.58	1.83	33.71	
	405		2 Nov 54					0.50	2.80	1.39	14.11	
	406		4 Nov 54					0.97	3.00	1.22	19.05	
Unnamed	209	Sandia Lab- oratories	1959	Alluvium (Albuquer- que)	TNT	256	116.10	3.87	±5.00	1.16	26.76	30
Sandia Series I	2	Sandia Lab-	21 Jan 59	Alluvium	TNT	256	116.10	2.90	4.61	2.40	60.77	19
	3	oratories	26 Jan 59	(Nevada				4.85	3.45	0.54	10.42	
	8		20 Jan 59	Test Site				1.94	4.00	2.23	42.16	
	9		23 Jan 59	Area 10)				2.90	4.31	2.18	54.65	
	10		23 Jan 59					3.87	4.08	1.25	30.95	
	11		24 Jan 59					4.85	1.99	0.12	6.68	
	12		27 Jan 59					5.81	2.85	0.70	7.25	
	15		16 Dec 58?					7.74	1.27	0.14	0.88	
	16							3.87	4.33	2.04	62.86	
	17		15 Dec 58?					5.81	1.73	0.52	1.56	
Sandia Series II	1*	Sandia Lab-	Aug 59,	Alluvium	TNT	256	116.10	9.08	9.45	-0.19	-16.54	19
	2*	oratories	Sep 59	(Nevada				8.69	11.49	-0.25	-30.55	
	3*			Test Site				7.96	9.85	-0.31	-33.61	
	4			Area 10)				7.77	0.72	0.35	0.45	
	5							7.10	0.92	0.09	0.51	
	6							6.89	1.34	0.30	4.81	
	7							6.00	2.48	0.31	3.43	
	8							5.79	3.07	0.49	8.41	
	9							5.00	4.36	0.80	20.27	
	10							4.91	4.30	1.39	30.50	
	11							3.99	4.48	1.66	47.29	
	S-12							0.00	2.61	0.76	4.56	
	S-13							0.00	2.54	0.79	7.56	
Toboggan	E 1a	Sandia Lab-	23 Nov 59	Playa (Yucca	TNT	8*	3.63*	0.00	0.47	0.28	0.07	36
	E 1b	oratories	23 Nov 59	Lake)				0.00	0.45	0.20	0.05	
	E 1c		24 Nov 59					0.00	0.40	0.20	0.04	
	E 2a		24 Nov 59					0.15	0.78	0.34	0.33	
	E 2b		24 Nov 59					0.15	0.69	0.32	0.23	
	E 2c		24 Nov 59					0.15	0.74	0.44	0.33	
	E 3a		24 Nov 59					0.30	0.85	0.49	0.44	
	E 3b		24 Nov 59					0.30	0.92	0.47	0.48	
	E 3c		24 Nov 59					0.30	0.82	0.53	0.44	
	E 3.5a		16 Jun 60					0.46	0.87	0.52	0.51	
	E 4a		24 Nov 59					0.61	1.05	0.54	0.75	
	E 4.5a		18 Jun 60					0.76	1.14	0.45	0.78	
	E 4b		24 Nov 59					0.61	1.09	0.59	0.97	
	E 4.5b		18 Jun 60					0.76	1.01	0.31	0.37	
	E 4c		24 Nov 59					0.61	1.12	0.55	1.03	
	E 5a		14 Nov 59					0.91	1.12	0.24	0.48	
	E 5b		15 Nov 59					0.91	1.22	0.55	1.10	
	E 5c		15 Nov 59					0.91	1.12	0.20	0.39	
	E 5.5a		18 Jun 60					1.07	0.96	0.10	0.20	
	E 6a		15 Nov 59					1.22	0.58	0.06	0.04	
	E 6b		15 Nov 59					1.22	0.46	0.04	0.01	
	E 6c		15 Nov 59					1.22	0.73	0.03	0.06	
	E 6.5a		18 Jun 60					1.37	--	--	--	
	E 7a		18 Jun 60					1.52	--	--	--	
Little Ditch	1 C	Sandia Lab-	12 Nov 59	Alluvium	TNT	8*	3.63	0.30	0.85	0.37	0.33	25
	1 C 8	oratories	29 Jun 59	(Albuquer-				0.30	0.94	0.34	0.27	
	1 D		10 Nov 59	que)				0.46	1.08	0.43	0.58	
	IV 1-1.5		11 Apr 60					0.46	1.18	0.3	0.63	
	IV 2-1.5		14 Apr 60					0.46	1.07	0.21	0.28	

(Continued)

* Data not used in the statistical analysis.

Table B1 (Continued)

Series Name	Shot Designation	Sponsor	Date	Medium	Type of Explosive	Charge Weight lb	Charge Weight kg	Burial Depth m	Apparent Crater Radius m	Apparent Crater Depth m	Apparent Crater Volume m^3	Source
Little Ditch (Continued)	IV 3-1.5	Sandia Laboratories	18 Apr 60	Alluvium (Albuquerque)	TNT	8*	3.63	0.46	1.14	0.18	0.35	25
	IV 4-1.5		19 Apr 60					0.46	1.05	0.18	0.26	
	IV 5-1.5		21 Apr 60					0.46	0.96	0.12	0.10	
	IV 6-1.5		25 Apr 60					0.46	1.05	0.37	0.42	
	IV 7-1.5		27 Apr 60					0.46	1.10	0.55	0.76	
	IV 8-1.5		28 Apr 60					0.46	0.99	0.15	0.19	
	IV 9-1.5		3 May 60					0.46	1.04	0.37	0.50	
	IV 10-1.5		13 May 60					0.46	1.10	0.24	0.37	
	I E		25 Nov 59					0.61	1.14	0.15	0.31	
	P 2A		12 Nov 59					0.61	1.11	0.34	0.48	
	P 2B		23 Nov 59					0.61	1.08	0.21	0.34	
	P 2C		5 Apr 60					0.61	1.19	0.55	1.14	
	P 8A		18 Nov 59					0.61	1.05	0.43	0.54	
	IV 1-2.0		11 Apr 60					0.61	1.02	0.15	0.22	
	IV 2-2.0		15 Apr 60					0.61	1.17	0.21	0.41	
	IV 3-2.0		18 Apr 60					0.61	1.16	0.18	0.36	
	IV 4-2.0		20 Apr 60					0.61	0.99	0.18	0.27	
	IV 5-2.0		21 Apr 60					0.61	1.18	0.24	0.51	
	IV 6-2.0		26 Apr 60					0.61	1.13	0.49	0.81	
	IV 7-2.0		27 Apr 60					0.61	1.07	0.43	0.65	
	IV 8-2.0		2 May 60					0.61	1.05	0.37	0.57	
	IV 9-2.0		3 May 60					0.61	1.20	0.21	0.83	
	IV 10-2.0		12 May 60					0.61	1.16	0.30	0.56	
	1 F		18 Feb 60					0.76	1.23	0.52	0.99	
	IV 1-1.2		14 Apr 60					0.76	1.05	0.30	0.37	
	IV 2-2.5		15 Apr 60					0.76	1.13	0.30	0.54	
	14 3-2.5		19 Apr 60					0.76	1.17	0.18	0.37	
	IV 4-2.5		20 Apr 60					0.76	1.21	0.27	0.58	
	IV 5-2.5		25 Apr 60					0.76	1.19	0.61	1.08	
	IV 6-2.5		26 Apr 60					0.76	1.10	0.37	1.57	
	IV 7-2.5		28 Apr 60					0.76	1.14	0.49	1.00	
	IV 8-2.5		2 May 60					0.76	1.14	0.61	1.09	
	IV 9-2.5		12 May 60					0.76	1.23	0.30	0.65	
	IV 10-2.5		13 May 60					0.76	1.10	0.43	0.62	
	P 3-A		9 Nov 59					0.91	0.84	0.15	0.13	
	P 3-B		26 Jan 60					0.91	1.21	0.67	1.50	
	P 4-A		7 Dec 59					1.22	1.08	0.12	0.25	
	P 4-B*		27 Jan 60					1.22	1.37	0.67	1.88	
	IV 4-3.0		28 Jul 60					0.91	1.23	0.12	0.53	
	IV 5-3.0		28 Jul 60					0.91	1.23	0.12	0.73	
	IV 6-3.0		29 Jul 60					0.91	1.16	0.37	0.62	
	IV 1-4.0		21 Jun 60					1.22				
	IV 2-4.0		22 Jun 60					1.22	1.01	0.12	0.18	
	IV 3-4.0		23 Jun 60					1.22				
	III 0.5		8 Jun 60			256	116.10	0.97	3.08	1.37	18.21	
	III 0.75		17 Jun 60					1.45	3.26	2.13	25.85	
	III 1.00		13 Jun 60					1.94	3.38	1.68	27.84	
	III 1.25		19 Jul 60					2.42	3.57	1.74	34.26	
	G2-34		16 Jul 62					2.42	3.57	1.55	25.60	
	III 1.50		15 Jun 60					2.90	3.86	1.07	23.33	
	G2-35		18 Jul 62					2.90	3.63	1.49	33.19	
	III 2.0a		26 Jul 60					3.87	3.54	0.85	15.57	
	III 2.0b		22 Aug 60					3.87	3.63	0.79	12.40	
	III 1.25b		8 Aug 60					2.42	3.47	1.58	32.25	
Unnamed	--*	Sandia Laboratories	1960	Alluvium	TNT	5,000	2,268.00	0.00	5.64	1.45	83.53	30
Stagecoach	1	Sandia Laboratories	15 Mar 60	Alluvium (Nevada Test Site Area 10)	TNT	40,120	18,198.10	24.38	17.37	2.41	1,391.63	20
	2		19 Mar 60			40,240	18,252.60	5.21	15.39	7.19	2,368.70	
	3		25 Mar 60			40,070	18,175.40	10.42	17.86	8.90	4,094.62	
Scooter	--	Sandia Laboratories	13 Oct 60	Alluvium (Nevada Test Site Area 10)	TNT	987,410	447,881.70	38.10	46.88	22.71	74,813.11	21
Rowboat	7a*	LRL	26 Jun 61	?	TNT	278	126.10	4.54	6.74	0.88	--	37
	8a*		28 Jun 61			278	126.10	4.54	8.75	0.75	--	
Pre-Buggy II	F-1*	Nuclear Cratering Group	6 Aug 63	Alluvium (Nevada Test Site Area 5)	Nitromethane	1,000	453.60	6.04	6.92	3.60	222.57	22
	F-2*		6 Aug 63			1,000	453.60	6.04	6.46	3.60	170.75	
	F-3		6 Aug 63		TNT	950	430.91	5.64	6.43	3.35	196.80	
	F-4		6 Aug 63			950	430.91	5.59	6.74	3.29	214.08	
Unnamed series	62-60	Sandia Laboratories	19 Nov 63	Alluvium (Albuquerque)	TNT	64	29.00	2.13	2.10	0.82	4.90	28
	62-62		26 Nov 63			64	29.00	2.13	2.26	0.62	5.15	
	62-64		2 Dec 63			64	29.00	2.13	2.10	0.62	4.59	
Air Vent	III 1A	Sandia Laboratories	31 Jan 64	Playa (Frenchman Flat)	TNT	64	29.03	0.00	1.04	0.48	0.68	31
	III 1B		31 Jan 64			64	29.03	0.00	1.04	0.55	0.74	
	III 1C		31 Jan 64			64	29.03	0.00	0.99	0.55	0.65	
	III 1D		31 Jan 64			64	29.03	0.00	1.07	0.57	0.80	
	III 2A		11 Jan 64			1,000	453.60	0.00	2.85	1.30	12.52	
	III 2B		11 Jan 64			1,000	453.60	0.00	3.08	1.39	14.64	
	III 2C		13 Jan 64			1,000	453.60	0.00	2.72	1.30	12.46	
	III 3A		8 Jan 64			6,000	2,721.60	0.00	5.01	2.00	71.36	
	III 3B		9 Jan 64			6,000	2,721.60	0.00	5.34	2.11	76.54	
Flat Top	II	Sandia Laboratories	17 Feb 64	Playa (Frenchman Flat)	TNT	40,000	18,143.70	0.00	10.9	3.93	680.45	24
	III		17 Feb 64			40,000	18,143.70	0.00	11.83	5.67	1,070.38	

(Continued)

* Data not used in the statistical analysis.

Table B1 (Concluded)

Series Name	Shot Designation	Sponsor	Date	Medium	Type of Explosive	Charge Weight lb	Charge Weight kg	Burial Depth m	Apparent Crater Radius m	Apparent Crater Depth m	Apparent Crater Volume m^3	Source
Air Vent	I-1	Defense Atomic Support Agency/ Sandia Laboratories	14 Dec 63	Playa (Frenchman Flat) (Nevada Test Site Area 5)	TNT	40,000	18,143.70	5.24	14.51	6.85	2,052.97	31
	II-1*		30 Jan 64			256	116.12	-0.26	0.98	0.25	0.37	
	II-2A		30 Jan 64					0.00	1.69	0.73	2.70	
	II-2B		29 Jan 64					0.00	1.65	0.74	2.64	
	II-3		29 Jan 64					0.26	2.05	1.03	6.67	
	II-4		29 Jan 64					0.48	2.32	1.13	6.99	
	II-5A		28 Jan 64					0.97	2.69	1.26	12.06	
	II-5B		28 Jan 64					0.97	2.59	1.33	10.79	
	II-6		28 Jan 64					1.45	2.92	1.41	14.64	
	II-7A		27 Jan 64					1.94	2.99	1.33	14.32	
	II-7B		27 Jan 64					1.94	3 03	1.37	15.40	
	II-8		27 Jan 64					2.42	3.15	1.21	13.68	
	II-9A		24 Jan 64					2.90	3.35	1.11	13.76	
	II-9B		23 Jan 64					2.90	3.36	0.71	9.40	
	II-10A*		24 Jan 64					3.87	6.98	-1.16	-33.36	
	II-10B*		23 Jan 64					3.87	8.05	-1.26	-70.79	
	II-11A*		16 Jan 64					4.85	6.89	-1.25	-75.83	
	II-11B*		16 Jan 64					4.85	6.80	-1.34	-77.08	
	II-12*		17 Jan 64					5.81	6.71	-0.81	-53.18	
	II-13*		17 Jan 64					6.77	7.13	-0.41	-28.40	
	II-14*		17 Jan 64					7.74	7.53	-0.19	-25.49	
Pre Capsa	1-1	Sandia Laboratories	3 May 65	Alluvium (Albuquerque)	TNT	256	116.10	2.90	4.10	2.13	53.94	29
	2-1		6 Jun 65			256	116.10	2.90	3.91	2.05	50.49	
Calibration Shots of Row Craters (unnamed series)	C 2	Sandia Laboratories	14 Jun 66	Alluvium (Albuquerque)	TNT	64	29.03	1.83	2.43	1.20	12.03	26
	C 3		14 Jun 66			64	29.03	1.83	2.51	1.35	14.27	
	1		1 Jun 66			64	29.03	1.83	2.49	1.31	12.86	
Calibration Shots of Row Craters (unnamed series)	6-1	Sandia Laboratories	7 Oct 66	Alluvium	TNT	64	29.03	1.83	1.20	1.20	10.02	27
	7-1		11 Oct 66					2.13	2.35	0.98	9.00	
	8-1		18 Oct 66					2.13	2.55	1.21	14.53	
	9-1		21 Oct 66					1.83	2.56	1.30	11.64	
	10-1		25 Oct 66					1.83	2.43	1.49	11.47	
Capsa	1	Sandia Laboratories	16 Aug 66	Alluvium (Albuquerque)	TNT	1,000	453.60	4.57	5.74	2.16	114.54	30
	2		18 Aug 66					3.81	5.52	3.13	137.05	
	3		24 Aug 66					3.05	5.45	3.20	129.04	
	4		26 Aug 66					5.33	5.84	2.15	111.29	
	5		31 Aug 66					4.57	6.00	2.16	118.14	
	6		2 Sep 66					5.33	6.01	3.22	168.09	
	7		13 Sep 66					3.05	4.91	2.78	103.67	
	8		16 Sep 66					3.81	5.92	3.24	163.70	
	9		21 May 68					3.81	5.62	3.18	151.18	
	10*		29 May 68					3.81	5.91	3.45	183.21	
	11*		13 Jun 68		Nitromethane	30,478	13,824.60	14.60	17.38	8.76	3,447.46	
	12*		25 Jul 68		Comp. B	977	443.20	3.81	6.06	2.88	162.45	
	13*		25 Jul 68		Nitromethane	981	445.00	4.57	5.89	2.94	146.74	
TTR-211	40	Sandia Laboratories	11 Aug 66	Playa (Test Range)	TNT	64	29.03	1.22	2.22	1.27	7.36	32
	47		18 May 67			64	29.03	1.52	2.43	1.16	9.23	
	48		24 May 67			64	29.03	1.83	2.56	1.27	10.45	
	49		8 Jun 67			64	29.03	2.13	2.34	0.92	5.83	
TTR 211	51	Sandia Laboratories	7 Jul 67	Playa (Tonopah Test Range)	TNT	64	29.03	0.00	1.10	0.47	0.73	32
	52		10 Aug 67			1,000	453.60	0.00	2.86	1.26	11.30	
	53		9 Jan 68			64	29.03	0.00	0.98	0.45	0.57	
	54*		19 Jan 68			8	3.63	0.91	1.11	0.30	0.46	
	55		21 Mar 68			256	116.12	2.90	3.63	1.48	25.68	
	56		20 Apr 68			1,000	453.60	0.00	3.01	1.46	16.79	
	42		25 Oct 66			64	29.03	2.10	2.23	0.89	5.52	33

* Data not used in the statistical analysis.

(Sheet 4 of 4)

APPENDIX C: DITCH DIMENSIONS FROM HIGH-EXPLOSIVE ROW-CHARGE DETONATIONS IN ROCK AND SOIL

Table C1

Ditch Dimensions from High-Explosive Row-Charge Detonations in Rock and Soil

Series Name	Shot Designation	Sponsor	Date	Medium	Type of Explosive	Charge Weight lb	Charge Weight kg	Depth of Burial m	Spacing Between Charges m	Average Apparent Crater Width m	Average Apparent Crater Depth m	Average Apparent Crater Volume m^3	Saddle Width at Charge	Saddle Depth at Charge	Source
Toboggan	A-1	Sandia Laboratory	Spring 1959	Playa (Nevada Test Site - Yucca Lake)	TNT	6 each at 8	6 each at 3.63	0.61	0.91	3.05	0.62	5.07	--	--	36
	B-2					6 each at 8	6 each at 3.63	0.61	1.07	2.16	0.61	5.30	--	--	
	C-3					6 each at 8	6 each at 3.63	0.61	1.22	2.13	0.50	4.54	--	--	
	D-4					6 each at 256	6 each at 116.1	1.93	3.87	7.01	1.59	155.94	--	--	
	E-5					6 each at 8	6 each at 3.63	0.61	1.52	1.77	0.62	4.33	--	--	
	F-6					6 each at 8	6 each at 3.63	0.61	1.83	1.98	0.43	One charge misfired			
Little Ditch	II A-2	Sandia Laboratories	17 May 60	Alluvium (Albuquerque)	TNT	7 each at 8	7 each at 3.63	0.00	0.61	1.31	0.22	0.68	1.00	0.62	25
	II C-1.5		22 Jun 59					0.30	0.46	2.01	0.49	1.92	1.00	0.97	
	II C-2.5		16 Jul 59					0.30	0.76	1.86	0.49	2.71	1.00	0.90	
	II C-3		01 Sep 59					0.30	0.91	1.52	0.33	1.89	1.00	0.94	
	II C-4		14 Oct 59					0.30	1.22	1.68	0.37	2.78	1.04	0.60	
	II C-5		05 Oct 59					0.30	1.52	1.37	0.24	1.81	0.69	0.60	
	II C-5B		24 Sep 59					0.30	1.52	1.29	0.21	1.68	0.48	0.40	
	II C-7		16 Oct 59					0.30	2.13	--	0.19	2.55	0.07	0.03	
	II D-3		10 Nov 59					0.46	0.91	2.16	0.49	3.79	1.00	1.00	
	II D-3.5		9 Mar 60					0.46	1.07	1.86	0.53	3.89	0.95	0.94	
	II E-3.0		9 Dec 59					0.61	0.91	2.53	0.53	5.44	1.00	0.94	
	II E-4.0		10 Mar 60					0.61	1.22	2.35	0.73	7.61	0.97	0.92	
	II E-5.0		24 May 60					0.61	1.52	1.83	0.49	5.23	0.77	0.78	
	II E-7.0		27 May 60					0.61	2.13	1.62	0.26	3.65	0.42	0.31	
	II F-3.5		13 Nov 59					0.76	1.07	2.44	0.56	5.77	1.00	0.95	
	II F-4.0		11 Mar 60					0.76	1.22	2.45	0.64	7.39	1.00	1.00	
	II F-4.5		10 Mar 60					0.76	1.37	2.44	0.70	9.37	1.00	1.00	
	II G-3.0		29 Jan 60					0.91	0.91	2.84	0.73	6.79	1.00	1.00	
	II G-3.5		10 Nov 59					0.91	1.07	2.71	0.55	6.34	1.00	1.00	
	II G-4.0A		11 Dec 59					0.91	1.22	2.47	0.37	4.69	0.98	1.00	
	II G-4.0C		16 Feb 60					0.91	1.22	2.75	0.79	9.48	1.00	1.00	
	II G-4.0B		4 Apr 60					0.91	1.22	2.89	0.85	10.81	1.00	1.00	
	II G-4.5		19 Feb 60					0.91	1.37	2.58	0.78	10.56	1.00	0.96	
	II G-4.5		25 Feb 60					0.91	1.37	2.58	0.73	10.75	1.00	0.92	
	II G-6.0		4 Mar 60					0.91	1.83	2.34	0.59	10.18	0.90	0.86	
	II G-8.0		9 Mar 60					0.91	2.44	1.94	0.37	7.45	0.40	0.41	
	II G-9.0		25 May 60					0.91	2.74	Same as II J: 7.0 with mounds between charges					
	II H-4.0		28 Mar 60					1.07	1.22	2.92	0.64	8.10	1.00	1.10	
	II J-3.5		3 Mar 60					1.22	1.07	3.08	0.78	10.13	1.00	1.04	
	II J-4.0		6 Apr 60					1.22	1.22	3.03	0.42	6.93	1.02	1.21	
	II J-5.0		2 Jun 60					1.22	1.52	2.44	0.59	7.82	1.00	1.05	
	II J-6.0		14 Mar 61					1.22	1.83	1.56	0.15	3.81	0.81	1.11	
	II J-7.0		20 May 60					1.22	2.13	Fallback filled crater leaving an uneven surface at original ground level					
	II L-4.0		1 Jun 60					1.52	1.22	2.87	0.53	7.71	0.99	1.06	
	II L-4.0B		20 Mar 61					1.52	1.22	Mound with maximum height of 0.66 m					
	IV 14.3-9.52		17 Aug 60			8 each at 256	8 each at 116.1	2.90	4.36	8.78	1.98	372.31	1.00	1.00	
	V 15.87-9.52		30 Dec 60			8 each at 256	8 each at 116.1	2.90	4.84	7.47	1.83	298.08	1.00	1.00	
	II K-3.5A		1 Mar 61			9 each at 8	9 each at 3.63	1.37	1.07	2.84	0.20	7.22	0.98	1.03	
	II K-3.5B		6 Mar 61			9 each at 8	9 each at 3.63	1.37	1.07	2.96	0.10	6.14	0.84	1.11	
	II K-4.0		9 Mar 61			9 each at 8	9 each at 3.63	1.37	1.22	2.59	0.32	7.34	0.97	1.02	

(Continued)

Table C1 (Concluded)

Series Name	Shot Designation	Sponsor	Date	Medium	Type of Explosive	Charge Weight lb	Charge Weight kg	Depth of Burial m	Spacing Between Charges m	Average Apparent Crater Width m	Average Apparent Crater Depth m	Average Apparent Crater Volume m^3	Saddle Width at Charge	Saddle Depth at Charge	Source
Rowboat	1	LRL	2 Jun 61	Alluvium (Nevada Test Site Area 10)	TNT	4 each at 278	4 each at 126.1	3.63	4.36	9.17	1.77	--	--	--	37
	2		5 Jun 61					3.63	4.36	8.78	2.01	--	--	--	
	3		13 Jun 61					3.63	6.53	7.47	0.91	--	--	--	
	4		15 Jun 61					3.63	6.53	7.68	1.13	--	--	--	
	5		20 Jun 61					5.43	4.36	3.99	0.43	--	--	--	
	6		22 Jun 61					5.43	4.36	4.11	0.27	--	--	--	
	7		26 Jun 61					4.54	5.46	4.27	0.30	--	--	--	
	8		28 Jun 61					4.54	5.46	5.49	0.67	--	--	--	
TTR-211	1	Sandia Laboratories	12 May 64	Playa (Tonopah Test Range)	TNT	6 each at 64	6 each at 29.0	1.52	2.44	7.02	1.98	28.52	--	--	30
	2		12 May 64			6 each at 64	6 each at 29.0	1.83	2.44	6.22	1.14	13.71	--	--	
	3		12 May 64			6 each at 64	6 each at 29.0	2.13	2.44	0.55	0.03	--	--	--	
	10		20 Aug 64			11 each at 64	11 each at 29.0	1.83	2.44	5.50	1.48	127.00	--	--	33
	13		3 Mar 65			11 each at 64	11 each at 29.0	1.83	2.44	5.16	1.20	101.46	--	--	
	16		27 May 65			5 each at 64	5 each at 29.0	2.10	1.60	6.11	1.76	56.97	--	--	
	41		5 Oct 66			2 each at 64	2 each at 29.0	1.83	2.44	5.10	1.27	18.60	--	--	
	43		18 Nov 66			25 each at 64	25 each at 29.0	1.83	2.44	5.59	1.48	286.45	--	--	
	44		22 Nov 66			5 each at 64	5 each at 29.0	1.83	2.44	5.30	1.53	55.30	--	--	
	45		24 Feb 67			11 each at 64	11 each at 29.0	2.10	1.60	6.36	2.00	136.57	--	--	
	46		27 Mar 67			2 each at 64	2 each at 29.0	2.10	1.60	5.56	1.57	22.46	--	--	
Pre Capsa	3	Sandia Laboratories	19 Mar 65	Alluvium (Albuquerque)	TNT	2 each at 256	2 each at 116.1	2.90	4.15	7.77	1.89	86.51	--	--	29
	4		14 Jun 65			3 each at 256	3 each at 116.1	2.90	4.15	8.44	2.20	130.37	--	--	
	5		27 May 65			5 each at 256	5 each at 116.1	2.90	4.15	8.78	2.01	216.88	--	--	

APPENDIX D: NOTATION

Crater and Ditch Dimensions (All in Metres)

B	Charge burial depth
D	Maximum apparent depth of single crater
D_r	Maximum apparent depth of row crater
L	Ditch length from first to last charge location
R	Average apparent radius of single crater
R_r	Average apparent half-width of row crater at charge locations
S	Spacing between charges in a row shot
x	Generalized linear crater dimension

Other Crater and Ditch Design Parameters

a	Reciprocal of scaling exponent
c_b	Coefficient for charge burial depth, metres/kilogram$^{1/a}$
c_d	Coefficient for apparent depth of single crater, metres/kilogram$^{1/a}$
c_r	Coefficient for apparent radius of single crater, metres/kilogram$^{1/a}$
c_s	Coefficient for spacing between charges in a row shot, metres/kilogram$^{1/a}$
c_v	Coefficient for apparent volume of single crater, cubic metres/kilogram$^{3/a}$
c_x	Coefficient for linear crater dimension, metres/kilogram$^{1/a}$
n	Number of charges in a row shot
w	Single or individual charge weight, kilograms
V	Apparent volume of single crater, cubic metres

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Explosive ditching with TNT, by Arno M. Muller [and] Hendrik D. Carleton. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1977.

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